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12–15 April 1988
A DECADE OF UV ASTRONOMY WITH THE IUE SATELLITE.

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Editorial Note
These Proceedings are published in two volumes, containing invited and poster papers on the topics indicated below. Some poster papers were selected for oral presentation and these are indicated as 'Contributed Papers'. For convenient reference each volume contains the full list of participants.

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X-ray and Cataclysmic Binary Systems
Binary Stars, Circumstellar Matter and Mass Transfer
White Dwarf Stars
Stellar Activity
Stellar Atmospheres and Variable Stars

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Foreword

This commemorative symposium, co-sponsored by the National Aeronautics and Space Administration (NASA), European Space Agency (ESA) and Science and Engineering Research Council (SERC) and supported by the American Astronomical Society (AAS), has been organized to celebrate the tenth anniversary of the successful guest observer programme of the International Ultraviolet Explorer (IUE) satellite observatory.

A record number of astronomers participated in this meeting. In all 294 people registered, of which 71 were from outside the United States. This total is some 50% greater than any previous IUE conference. Among the participating observers were Professor Jorge Sahade, President of the International Astronomical Union, who gave the opening address, and Professor Bernard Burke, President of the AAS, who presented a paper on gravitational lensing.

In addition to the IUE users, the list of celebrants included Professor Reimar Lüst, ESA’s Director General, Professor Lennard Fisk, NASA Associate Administrator for Space Science, Professor Roger Bonnet, ESA’s Director of Scientific Programmes, Dr John Townsend, Director of Goddard Space Flight Center, and Dr Charles Pellerin, Director of NASA Headquarters’ Astrophysics Division.

By all accounts the symposium was a resounding success, featuring a score of invited guest speakers and some 160 poster presentations. High points included the optimistic notes expressed by Professor Lüst, Professor Fisk and Professor Bonnet, who all look forward to celebrating the 20th anniversary of IUE in another ten years!

The two volumes of these proceedings present recent IUE results and also reviews of some selected topics studied with this satellite observatory over the past decade. For comprehensive highlights of the research conducted with IUE, as well as its history and archival data, the reader is also referred to ‘Exploring the Universe with the IUE Satellite’ (D. Reidel, 1987).

On behalf of the Scientific Organizing Committee, I wish to thank the Local Organizing Committee, the Session Chairmen and all the participants for making the symposium such a rewarding experience, and would like to express our sincere appreciation to all those scientists, engineers, technicians and support personnel who made IUE a wonderful reality.

Yoji Kondo
Welcoming Address
Ladies and Gentlemen,

It is my privilege and my pleasure to be here with you today at the opening of this Symposium, organized to celebrate Ten Years of IUE Astronomy; ten years of the most successful astronomical space experiment ever undertaken.

The success of IUE is the success of a design, the success of a technology, also a success in terms of scientific output, altogether a brilliant achievement! I would go so far as to say that IUE embodies an outstanding victory for Man in his endeavour to learn more about the Universe.

IUE’s extraordinary scientific output can be measured in terms of the number of images taken, and in terms of the number and importance of research results published. Could we describe anything but extraordinary a total number of images in the order of 10,000, and approaching 1,500 papers published in refereed journals?

IUE has justifiably been described as ‘the most productive telescope in the Solar System’. And this has been possible because of the expedition and minimal bureaucracy that have characterized the utilisation of the satellite and of the archived data.

It would be difficult to find a field where IUE has not left an imprint. A large part of what has been achieved scientifically up to the beginning of 1986 is reviewed in the book* that appeared last year edited by Yoji Kondo, the present IUE Project Scientist. We also have at hand the Proceedings of the various IUE conferences held here at NASA and in Europe, either under the auspices of ESA or joint NASA, ESA and SERC sponsorship.

We should perhaps emphasize that the IUE story reflects the efficient and determined association of these three agencies — NASA, ESA and SERC — and the uniring and devoted effort of a large number of scientists and technicians. It provides a most valuable experience of thinking and working together that is helping and encouraging cooperation in further scientific space adventures, which will continue to make our times most exciting and rewarding.

I remember the years prior to the launch of the IUE satellite, when the astronomical community was asked to submit research proposals for the first year of operations. Astronomers did not know what to expect and the response reflected the sort of skepticism that was prevalent. So few proposals were received for the first year that even I was assigned observing time, 16 shifts in total!

The excellence of IUE’s performance was soon evident and the result is that nowadays the available observing time is heavily oversubscribed, with proposals pouring in at each deadline for submission. We can justly say that now, after the experience of ten years, astronomers could not conceive of life without an IUE satellite orbiting in space!

Up to now the number of astronomers that have used IUE for their research purposes surpasses 800 at Goddard, and 700 at Vilspa. These figures represent a very substantial fraction of the most active astronomers in the United States and in Europe respectively. I should add here that ten percent of these scientists are from outside the United States and Europe.

On behalf of the International Astronomical Union I would like to express the admiration and the gratitude of the astronomical community to all those who have been and who continue to be responsible for the planning, construction, operation and organization, for all the different links of the structural chain related to the IUE satellite .... Happy Birthday IUE!
Invited Papers
OBSERVING SN 1987A WITH IUE

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ABSTRACT

IUE observations of SN 1987A began promptly after the discovery. They have been especially useful in determining which star exploded, and its stellar evolution before the explosion. When the supernova turns transparent in the ultraviolet, probably in 1988, the ultraviolet spectra will provide important chemical information about the interior of the massive star.

Keywords: SN 1987A, supernovae, spectroscopy

1. INTRODUCTION

The presence of the IUE satellite, and the prescience of its management, have helped provide a unique set of data on the most important event in the study of supernovae since the day Fritz Zwicky was born. Because the IUE was operating, and a target-of-opportunity proposal in place, an orderly, though very exciting, series of observations was carried out starting on the day of discovery, February 24, 1987, and has been sustained through the past year. The effectiveness of this work is due in no small part to the encouragement of Project Scientist Yoji Kondo, and the hard work by the entire IUE Observatory staff at Goddard Space Flight Center, especially George Sonneborn, and the productive cooperation with our European colleagues, including Panagia, Gilmozzi, Cassatella, Wamsteker, and Fransson. Another source of help and inspiration was the high-minded cooperation of many IUE users who gracefully stepped aside so that these data could be collected in a timely way. This was often inconvenient for them, and I am especially grateful for their understanding and good will.

Supernova 1987A in the Large Magellanic Cloud has moved the subject of supernovae from plausible argument (hand waving) to observational demonstration (science) in a number of areas and the IUE observations have helped in key areas. While the supernova was the first visible to the unaided eye since Kepler's 1604 supernova, retinal observations have not proved the most novel. Instead, the advances in technology, including geosynchronous satellites, have provided the data for real insight.

We have long believed, without powerful evidence, that one class of supernova explosions (Type Ia) results from massive stars, which release $10^{53}$ ergs of neutrinos as their iron cores collapse to become neutron stars. The essence of this picture was sketched by Baade and Zwicky in 1933 (ref. 1), shortly after the discovery of the neutron.

Testing this part of the picture has involved the underground neutrino detectors, which caught enough of the neutrinos to make a convincing case that we understand the binding energy of a neutron star, as well as the temperature and duration of the neutrino emission (ref. 2). It has also involved the IUE, which helped in identifying the massive star that exploded, both directly through astrometry and indirectly through the behavior of the UV output. This is the first time that a pre-supernova star has been observed, and the first time we have known the name of the victim: Sanduleak -69 202.

Supernovae are also widely believed to play a central role in the chemical enrichment of the universe. When the star destroys itself, the accumulated products of stellar energy generation such as helium, nitrogen, carbon, oxygen, calcium and silicon are dispersed into the interstellar gas along with the elements synthesized in the explosion. The chemistry of the stellar interior can now be probed by infrared observations (ref.3), and the gamma ray detections (ref. 4) provide strong proof that radioactive $^{56}$Ni is produced in the explosion. The IUE observations of SN 1987A helped establish the history of for Sanduleak -69 202, and it has turned out to be a challenging and surprising test of stellar evolution theory.

2. OBSERVATIONS

The first IUE spectra of SN1987A were taken from Goddard on the afternoon of Tuesday, February 24. The first frame of 15 seconds duration was heavily overexposed, and good low dispersion spectra were eventually obtained in about 1.5 second. The initial spectra were unlike the other IUE spectra of supernovae (ref. 5,6), and changed very rapidly in the first few days of observation as shown in Figure 1.
The combined optical and UV spectrum for the first day of observations is shown in Figure 2.

Figure 2. A combined optical and UV spectrum for 24 February 1987.

This spectrum shows that the supernova had distinct hydrogen Balmer lines; the identifying criterion for SN II. The P-Cygni lines in the UV and optical indicated an initial expansion velocity near 30 000 km/sec and a temperature near 14 000 K, but this declined very rapidly as the supernova atmosphere expanded and cooled adiabatically. The effect on the ultraviolet flux was profound, as the cooling and the onset of powerful line blanketing combined to reduce the UV flux from the supernova by a factor of 1000 in the first three days, as shown in Figure 3.

Despite the differences between SN 1987A and the Type II supernovae that come from red giant stars, hydrogen in the atmosphere make both amenable to modelling. This is of special interest because SN II might be useful as distance indicators, even if they are not standard candles, by comparing the expansion velocity with an angular size inferred from the flux and temperature (ref. 13). Models for the optical and UV should help establish the run of density with velocity in the atmosphere, the helium abundance at maximum light, and the luminosity of the star for determining distances. While the distance to the LMC is not the goal,

Although high-dispersion IUE observations of the interstellar medium were obtained in the first days, the rapid decline of UV flux made this fruitful probe of the interstellar gas a brief one (ref. 7, 8).

2.1 Clues to the Progenitor

Several features of this supernova were remarkable, as emphasized in the early reports (ref. 9,10,11). Not only were the velocities higher and the color evolution rapid, but the luminosity of the supernova was lower than for other SN II, and did not reach its peak for nearly 3 months, on May 20. All of these properties can be understood as effects of the deposit of the usual $10^{51}$ ergs in the envelope of a blue supergiant, rather than the red supergiant which matches the properties of most SN II progenitors (ref. 12). In this case, the adiabatic losses in expansion are more severe, and radioactivity plays a larger role in providing energy during the rise to maximum and dominates the energy balance on the exponential tail shown in Figure 4.
success in modeling the atmosphere of SN 1987A would be a good sign for the application of this technique to more distant objects. An early attempt by my graduate student, Ronald Eastman, is shown in Figure 5. The resemblance is encouraging, but more work needs to be done.

The identification of SK -69 202 as the progenitor was surprising, since conventional wisdom holds that SN II come from red supergiants. But the destruction of this star, a B3 Ia supergiant, radiating $10^5$ solar luminosities with surface temperature near 15 000 K, and an extent of only 40 solar radii, would produce the observed unusual velocities, color changes, and luminosity.

Available images showed that SK -69 202 had a close neighbor, about 3" to the northwest. As the supernova faded in the UV, the story took an amusing twist as the line-by-line files from IUE clearly showed that after the supernova faded, there were spectra of two hot stars in the center of the aperture. It seemed likely that these two were the Sanduleak star and its neighbor, so that neither was the supernova progenitor. However, careful analysis of better optical data showed (ref. 15, 16) that there were actually three stars at the site of the explosion, all within the point spread function of the IUE.

To unravel this puzzle, Sonneborn, Aitner, and I (ref. 17) and independently Gilmozzi et al. (ref. 18) dissected the IUE spectrum in the spatial direction and made careful measurements of the separation of its two components. The astrometry showed that the separation was just that of the two other stars: that SK -69 202 had in fact disappeared, and was the best identification for the supernova progenitor.

2.3 Circumstellar Matters

The weak radio emission from SN 1987A (ref. 19) was interpreted (ref. 20) as arising from a shock in the low density blue supergiant wind of SK -69 202. An interesting aspect of the evolution of this star has recently been revealed by the IUE observations. After a few months, the short wavelength IUE spectra began to show evidence for narrow emission lines, as shown in Figure 6.
The observed lines are principally those of nitrogen, ranging from $N \, V$ to $N \, III$. The observed velocities are low, and the velocity widths of the lines are unresolved at the low dispersion, implying velocities less than 1000 km/sec. All of these clues point toward a circumstellar origin for the emission lines. First, the fact that we can see the emission, while the supernova photosphere is opaque to the UV implies that the source of the emission is outside the expanding star. Second, the low velocities do not correspond to the debris, where the characteristic velocities are a few thousand km/sec. The great strength of the nitrogen lines is consistent with the chemical composition of material that might result from mass loss for a massive star (ref. 21, 22).

The excitation of this circumstellar shell would be the result of the UV flash that took place when the shock traversing the Sanduleak star hit the surface. This initial pulse of energy would have been very hot ($10^5$ K) and brief (1 hour). Since the supernova was not discovered on the day of the neutrino burst, but the day after, the declining UV seen on 24 February must have been just the tail of this violent UV flash.

The observed UV flux from the circumstellar shell has been increasing with time from the first detection in the summer of 1987 to the current epoch, 600 days after the explosion. A plausible picture for the shell would be that it is far enough from the supernova site that light travel times are important in determining the observed flux. In that case, a dimension of order $10^{18}$ cm (1 light year) is indicated by the duration of the increase, since we are seeing the effects of the initial UV flash echoed to us from the circumstellar shell. The spatial extent of this shell would be of order 2", not yet measurable with IUE.

Because of the increasing flux, we have been able to make high dispersion IUE measurements of the circumstellar lines. They remain unresolved at 30 km/sec resolution as shown in Figure 7.

The observed line ratios are consistent with a density of order $10^6$ in the emitting gas, and ground based observations of narrow [O III] help determine the temperature at about 65 000 K (ref. 23). With the
physical conditions reasonably well determined, we can determine the chemical abundances. We find N/C is about 10, a factor of 40 above the solar value.

High nitrogen abundance was also found in the circumstellar matter of an earlier SN II with IUE (ref. 24). There, the explosion took place while the star was a red supergiant; here, the circumstellar matter was evidently ejected from the star as a red supergiant, but the star evolved to the blue before exploding. Thus the IUE observations help establish the history of SK -69 202, 20,000 years before it became famous.

Matching the path in the H-R diagram and the chemical composition of the circumstellar matter has proved a challenging task for theorists, who were already struggling with the question of why the star exploded as a blue supergiant. The evolution from blue (on the main sequence) to red (as a mass-losing red supergiant) back to the blue (to explode as a B3 Ia star) has been examined by Saio, Kato, and Nomoto (ref 25). Key ingredients seem to be the lower heavy element abundance in the LMC and substantial mass loss as a red supergiant. The possible abundance peculiarities at the supernova's surface suggested by Williams (ref. 26) might be related to structural changes in the star at the time of extensive mass loss.

While the details remain to be worked out, it is clear that the IUE observations have been exceptionally helpful in tracing the evolution of Sk -69 202 in the millennia before the explosion.

One prediction of this picture is that the rapidly expanding debris, moving at 1/10 c, will strike the circumstellar shell, out at 1 light year, in about 10 years. So for the end of the century, we may expect a recrudescence of SN 1987A, with a hot shock interaction producing copious X-rays and perhaps another blast of UV emission. While I hope that all of us are able to observe this event, I also hope that we will do it with a successor to IUE, rather than with a satellite which will be 20 years old!

3. ACKNOWLEDGEMENTS

One of the great pleasures of studying SN 1987A has been the lively and stimulating discussion among the participants, and the cooperation of so many who supported the observations by adapting to a revised schedule. This generous spirit places a special obligation on those of us who are working on the data to do the best job we can, and to leave a unique set of data for future astronomers. RPK's research on supernovae is supported by NASA grants NAG5-645 and NAG5-841, and by NSF grant AST85-16537.

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CATACLYSMIC VARIABLES

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Abstract

Important progress has been made in the last few years in the understanding of the complex phenomena occurring in cataclysmic variables. An outstanding contribution to these advances has been provided by observations with the International Ultraviolet Explorer. The most recent results obtained in the specific cases of classical novae, old novae and recurrent novae are reviewed.

Keywords: UV spectra, cataclysmic variables, classical novae, recurrent novae

1. Introduction

The class of cataclysmic variables includes classical novae, recurrent novae, and dwarf novae. In recent years the definition has been extended to objects containing a magnetic white dwarf, such as AM Her-type stars and to nova-like stars. A common characteristic of cataclysmic variables is that they contain a white dwarf companion (although this is still being debated in the case of recurrent novae). The ultimate cause of the variability, sometimes manifesting itself in violent events, is also common in these objects and can be identified with mass accretion onto the compact companions.

In this paper we intend to highlight some of the major achievements recently obtained through the International Ultraviolet Explorer in the understanding of the physical processes occurring in cataclysmic variables, and in particular in classical and recurrent novae. Recent comprehensive reviews of the UV properties of cataclysmic variables can be found, for example, in Starrfield (1986), Starrfield and Snijders (1987), Starrfield and Sparks (1987), Cordova and Howarth (1987), and Friedjung (1988).

2. Classical Novae in outburst

Ultraviolet observations of classical novae in outburst have provided new information on fundamental parameters like the elemental abundances in the ejecta, and the energetics and dynamics of the outbursts.

In the last few years, abundance determinations of unprecedented accuracy have been obtained, especially in those cases in which the UV data could be complemented with simultaneous ground based spectrophotometric observations taken during the nebular phase. A broad wavelength baseline is essential for abundance studies because emission lines arising from different ionization stages of a given element can be observed, which leads to a precise diagnostics of the physical conditions in the line emitting regions and, in particular, of the ionization structure. Heavy elements abundance determinations in novae not only provide a crucial test for thermonuclear runaway theories, but also contain important information on the nature of the white dwarf companions. At present, abundances for CNO and heavier elements have been published for four out of the dozen classical novae observed with IUE: V1668 Cyg 1978 (Stickland et al. 1981), V393 Cra 1981 (Williams et al. 1985), V1370 Aql 1982 (Snijders et al. 1984, 1987), and N Mus 1983 (Krautter et al. 1984).

The first important result of these investigations is the confirmation that the total abundance in CNO elements is substantially larger than solar. These overabundances cannot be accounted for by thermonuclear runaway theories alone, since hydrogen burning through the CNO cycle is expected to change the isotopic abundance patterns of CNO elements while conserving the total CNO/(H + He) nuclear ratio by mass (Truran 1985). Instead, the large CNO overabundances can be understood...
provided the element enrichments are already present at the onset of the thermonuclear runaway. Such considerations have lead to the suggestion that the white dwarf companions of classical novae are C-O white dwarfs (unless large overabundances are observed also in elements like neon, oxygen and magnesium; see below). Enhanced CNO abundances in the envelope would be produced by shear-induced turbulent mixing between the white dwarf core material and the accreted layers (Kippenhahn and Thomas 1978; McDonald 1984).

A particularly important result is the recent discovery of a new class of novae, the "Neon novae" whose ejecta are characterized by abundance enhancements in elements like oxygen, neon, magnesium and aluminum relative to H, He and CNO nuclei (Starrfield, Sparks, Truran 1986). The first "IUE nova" which was reported to show neon enhancement is N Aql 1982, in which the Ne/He ratio by number was found to be 1.18, compared with 1.5x10^{-3} in the sun and other Pop. I objects (Snijders et al. 1984, 1987). Two additional objects of this kind have been reported: N Cra 1981 (Williams et al. 1985) and PW Vul = N Vul 1984 No. 2 (Starrfield, Sparks and Truran 1986; Gehrz et al. 1986; Andrilat and Houziaux 1985). In Nova Cra 1981 the Ne/He abundance ratio was about 0.1 (Williams et al. 1985), i.e. considerably less than in N Aql 1982. A major difficulty in the understanding of these abundance anomalies is that, even in the case of massive white dwarfs, the temperature in the shell would not reach the values needed for the CNO cycle to break out yielding Ne, Na, Mg and Al (Starrfield, Sparks and Truran 1986; Sugimoto et al. 1980). A natural explanation can be found, instead, if one assumes that the heavy elements represent a small fraction of core material from an underlying massive ONeMg white dwarf that has mixed through a hot hydrogen burning region and then ejected into space as a consequence of the thermonuclear runaway (Truran 1985; Williams et al. 1985; Starrfield Sparks and Truran 1986). The existence of ONeMg white dwarfs in nova systems was predicted by Law and Ritter (1983). Nomoto (1983) showed that ONeMg white dwarfs can be accounted for by single star evolution with an initial mass on the main sequence from 8 to 12 M\(_\odot\). The case of N Aql 1982 is discussed by Wiescher et al. (1986), who suggest that the observed overabundances in C and O, require the presence of a CO shell around a ONeMg white dwarf, while the enhancements of elements up to S and even Fe might be the result of high temperature rp-processes where also a break-out of the CNO cycle occurred.

The question why so a large fraction of novae are found to be ONeMg novae has been addressed by Truran and Livio (1986), who conclude that selection effects should be able to explain their high frequency. Having degenerate components more massive than C-O white dwarfs, a lower accumulated mass is needed to produce thermonuclear runaway, and

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Fig. 1: Oxygen abundance by number versus decline time \( t \), adapted from Pacheco and Codina (1985). IUE observations (triangles) confirm that fast novae have larger oxygen overabundances, compared with slow novae. Abundances for the "IUE novae" are from Williams et al. (1985) for N Cra 1981, Snijders et al. (1987) for N Aql 1982, Stickland et al. (1981) for N Cyg 1978, Hassall et al. (1988) for N Mus 1989, and Drechsel et al. (1988) for N Vul 1984 No. 1.

Fig. 2: Light curves (UV, optical, infrared and bolometric) for the fast nova N Aql 1982 (Snijders et al. 1987) and the moderately fast nova N Cyg 1978 (Stickland et al. 1981).
therefore the outburst frequency should be larger. Note also that abundance anomalies in elements like O, Ne and Mg are best detected in the UV, a spectral region which only in recent years has been made accessible.

Theoretical models predict that the main characteristics of the outbursts are determined by the amount of CNO material present at the base of the accreted envelope at the onset of the thermonuclear runaway. This applies, in particular, to the class speed, as discussed by Truran (1985). Using abundance determinations from optical data, de Freitas Pacheco and Codina (1985) show that, in agreement with the predictions, log [O/H] is larger for novae with smaller $t_\text{o}$, the decline time 3 mag from light maximum. IUE data support and strengthen the above result indicating the existence of clear correlation between oxygen abundance and decline time, as shown in Fig. 1 (adapted from de Freitas Pacheco and Codina).

The first nova observed by IUE for which evidence of dust formation was reported is N Aql 1982 (Snijders et al. 1984). This object, the second after N Cyg 1978 (Stickland et al. 1981) to be monitored regularly in a broad wavelength range, allows interesting comparisons to be made between the bolometric light curve and the UV, optical and infrared light curves (see Fig. 2, from Snijders et al. 1987). The optical light curve of N Aql 1982 has a minimum near day 55 (after maximum) and brightens again between days 90 and 140. The UV light curve is similar to the previous, but the minimum appears later, near day 77. On the contrary, the IR flux peaks in the period from days 29 to 156, i.e. in antiphase with the UV and optical fluxes, indicating that dust formation was taking place (Snijders et al. 1984, 1987). In addition, the ultraviolet extinction law was found to be peculiar, with an absorption feature peaking at 2500 Å. Snijders et al. (1987) suggested that the dust in N Aql 1982 is composed of silicate and metallic grains and of carbon smokes and had a mass of at least $4 \times 10^{-6}$ M$_\odot$, and possibly as high as $2 \times 10^{-5}$ M$_\odot$. The mass of the dust is then comparable with the mass of the gas. There is good evidence that, during the dust formation stage, the gas phase in Nova Aql 1982 became considerably depleted in carbon, oxygen, magnesium, silicon and possibly iron (Snijders et al. 1987) and aluminum (Snijders, private communication). It is quite remarkable that, in spite of dust formation processes, the shape of the bolometric light curve of N Aql 1982 is similar to that of the moderately fast nova Cyg 1978 (Stickland et al. 1981), although the time behaviour of the fluxes in the different wavelength bands and the overall energy release was different in the two novae. A comparison between the light curves of these two novae is shown in Fig. 2.

Another aspect in which IUE observations have provided important and novel information is the dynamics of the ejection. Although the available IUE high resolution data have not been fully analyzed yet, it has been possible to discover that fast novae have very large expansion velocities of up to roughly $-10000$ Km/s in the ultraviolet lines, as found in the case of N Ser 1983 (Drechsel, Wargau and Rahe 1984) and of the neon novae N Aql 1982 (Snijders et al. 1984, 1987) and N Cra 1981 (Sion et al. 1986). Considerably smaller expansion velocities were found, on the contrary, in the moderately fast nova N Cyg 1978 (Cassatella et al. 1979) and in the slow nova N Vul 1984 No. 1 (Cassatella and Gonzalez Riestra 1988). The difference in velocity fields in a fast and a slow nova is illustrated in Fig. 3, for Nova Cra 1981 and N Vul 1984 No. 2, respectively. The larger expansion velocities in Neon novae are thought to be the consequence of having a smaller ejected mass, and a larger overall energy release during the outburst (Starrfield, Sparks and Truran 1986).
2. Classical novae in quiescence

The continua of old novae are generally peaked in the ultraviolet, and arise from the accretion disk around the white dwarf primaries. Unfortunately, out of the dozen old novae which would be accessible with IUE, only a few have been observed. Knowledge of the behaviour of these objects in the ultraviolet years or decades after the outbursts provides information on at least one important parameter: the mass accretion rate $\dot{M}$. A major problem, which has been a matter of controversy for some time, is the fact that the observed mass accretion rate in old novae, $\dot{M} \sim 10^{-7} - 10^{-9} M_\odot/yr$, is considerably larger than that predicted by models, $\dot{M} \sim 10^{-11} - 10^{-12} M_\odot/yr$. Should the mass accretion rate stay so high during the interoutburst phases, a strong compressional heating would operate in the white dwarf envelope, leading to ignition under weakly degenerate conditions. If so, no nova-type outbursts would be produced, unless the white dwarf mass approached the Chandrasekhar limit (Starrfield, Sparks and Truran 1986).

From the observational point of view, $\dot{M}$ is difficult to determine accurately. Basically, $\dot{M}$ can be determined in two ways: a) from the slope of the UV continuum and, b) from the disk bolometric luminosity $L(\text{disk}) = 0.5 G M \dot{M}/R$. In neither case would one be able to avoid the difficulty of taking into account the flux emitted below 1150 Å (although data for some cataclysmic variables are available from the Voyager experiment, see, e.g., Polidan and Holberg 1987). One additional uncertainty applicable to the former method, is that the slope of the continuum may also depend on the system inclination (Warner 1986) and/or on the white dwarf mass (Verbunt 1987). The IUE observations of dwarf novae so far available seem to support a dependence on the inclination: the high inclination systems T Aur and BT Mon show a flat UV continuum, while V Sge and DI Lac ($i \approx 0^\circ$) show hot UV continua (see Fig. 4). A compilation of mass accretion rates in old novae can be found in Verbunt and Wade (1984).

An extremely interesting scenario which would account for the discrepancy between observed and predicted mass accretion rates is the hibernation theory, described in a series of papers by Shara, Livio, Moffat and Orio (1986), Prialnik and Shara (1986), Livio and Shara (1987), Kovets, Prialnik and Shara (1988), and Livio, Shankar, and Truran (1988). Given a recurrence time of roughly $10^5$ yrs, the mass accretion rate would gradually decrease from some $10^{-7} - 10^{-8} M_\odot/yr$ (as actually observed) after the outburst, to values as low as $10^{-11} - 10^{-12} M_\odot/yr$ (hibernation). The decrease of $\dot{M}$ would be produced by an increase of the system separation as a direct consequence of the outburst (see the case of BT Mon 1939 reported by Schaefer and Patterson 1983). After some $10^4$ yrs of hibernation, the system separation would decrease again due to gravitational radiation or magnetic braking by a stellar wind. Roche lobe contact would then be restored, and the accretion rate would increase again to $10^{-7} - 10^{-8} M_\odot/yr$. This scenario is particularly interesting because it offers the possibility of including dwarf novae in the cyclic evolutionary sequence of classical novae, if it is true that their activity is produced by disk instabilities. Indeed, during the evolution preceding and following hibernation, the systems would approach critical mass accretion regimes, and experience dwarf nova outbursts. Another interesting feature of the model is that it would solve the problem of the discrepancy between the space density of classical novae indicated by sky surveys and that deduced, for example, from the nova frequency in M 31, or from theoretical considerations.

Fig. 4: Observed ultraviolet energy distribution of the high inclination old nova BT Mon ($i = 84^\circ$) compared with the low inclination system DI Lac ($i = 0^\circ$). Fluxes are in units of $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ A$^{-1}$. 
3. Recurrent novae

Recurrent novae are objects for which more than one nova-like outburst has been historically recorded. Just a few objects can be included in this class, especially nowadays that better classifications have been found for some of them. The best known class members are T CrB (outbursts in 1866 and 1946), RS Oph (outbursts in 1899, 1933, 1967 and 1985), and T Pyx (outbursts in 1890, 1902, 1944, 1966). The optical light curve of recurrent novae is similar to that of classical novae, but the amplitude of the variation is considerably smaller. This is ascribed to the presence of a cool giant in the system (see, e.g., the case of RS Oph and T CrB) which causes these objects to be brighter, at minimum, than classical novae.

There are two basic models to explain the outbursts of recurrent novae: thermonuclear runaway on a white dwarf companion, or events powered by a burst of matter from a red giant onto a main sequence companion. In both cases an accretion disk is required around the primary. If the primary is a main sequence star, the inter-outburst accretion rate is expected to be very low. If the secondary is a white dwarf, its mass is expected to be close to the Chandrasekhar limit, and a high accretion rate ($>2 \times 10^{-6}$ M$_\odot$/yr) is required between outbursts (Starrfield, Sparks and Truran 1985).

With the outburst of RS Oph in 1985, IUE provided the first opportunity of studying in detail a recurrent nova in the ultraviolet. Probably, the next opportunity will be offered by T Pyx, whose outburst is thought to be imminent. One of the most remarkable features of the spectral development of RS Oph during the 1985 outburst is the progressive narrowing of the emission lines, a fact already known from optical spectroscopy during previous outbursts (Pottasch 1967) and nicely confirmed by IUE observations (Cassatella et al. 1985; Snijders 1986). The narrowing of the emission lines is caused by the deceleration of the ejected matter by shock interaction with a preexisting extended envelope around the system, a remnant of previous outbursts, and continuously fed by the mass lost from the cool companion (Rosino, Taffara, Pinto 1960; Pottasch 1967). The interaction between the ejected material and the circumstellar gas has another important effect: the shocked gas is collisionally heated up to very high temperatures of the order of several million degrees, which accounts for the appearance of the forbidden lines from ions such as [Fe XI] 1467 and 2649 Â, and [Fe XII] 1349, 2406 and 2566 Â, all very strong in the ultraviolet, especially between days 50 to 80 after the 1985 outburst (Cassatella and Gonzalez Riestra 1985). In Fig. 5 we show the asymmetric profile of [Fe XI] 2648.7 Â. Apart from the solar corona, RS Oph is the first object in which such lines were observed in the ultraviolet. IUE high resolution spectra taken during the 1985 outburst provide evidence that mass ejection was not spherically symmetric, as demonstrated by the presence of blue and red-shifted components in the resonance and intercombination lines (Cassatella et al. 1985).

One of the most crucial pieces of information needed to distinguish between thermonuclear runaway and accretion events in the framework of current models, is the development of the bolometric light curve. This information is available, in a preliminary form for the 1985 outburst of RS Oph (Snijders 1986). Assuming a distance to RS Oph of 1.6 kpc, Snijders finds that the bolometric luminosity in the plateau region is consistent with the Eddington luminosity for a massive white dwarf. Also, he finds that the shape of the bolometric light curve is similar to that of fast classical novae. This would strongly support thermonuclear runaway as the cause of the outburst as in the model predictions by Starrfield, Sparks and Truran (1985). The high inter-outburst
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mass accretion rate required in this case is also supported by the high luminosity of the UV continuum before and after the outburst. A further argument in favour of the runaway model is provided by the relative C, N, and O abundances, which are similar to those of classical novae (Nussbaumer et al. 1988).

Another well studied recurrent nova is T CrB, a double-line spectroscopic binary with an orbital period of 227.53 days and $V_K$=23.32 km/s, values derived from radial velocity measurements in the absorption lines of the giant (Kenyon and Garcia 1986). However, the value of $V_K$, based on radial velocity measurements in the broad and structured Balmer lines (Kraft 1958) is uncertain, so that it is difficult spectroscopically to distinguish between a main sequence and a massive white dwarf accretor.

Another, less direct, but powerful way to get insight on the nature of the primary in T CrB is the regular monitoring in progress with IUE since 1979 (Cassatella et al. 1982, 1985). The IUE observations show a number of features which are best interpreted within the framework of white dwarf accreting models (Selvelli, Cassatella and Gilmozzi 1988). In first place, the bulk of the accretion disk luminosity is emitted in the UV, with negligible contribution in the optical range ($L(\text{UV}) \approx 2 \times 10^{32}$ ergs/s and $L(\text{opt}) \approx 10^{31}$ ergs/s). Both the high UV luminosity and the spectral distribution are hardly compatible with the presence of a main sequence star because this would require a very high accretion rate and, consequently, the disk would emit mostly in the optical. A further argument comes from considering the rather strong HeII 1640 A line ($L(\text{HeII}) \approx 1.2 \times 10^{32}$ ergs/s), indicative of a temperature in the boundary layer of the order of $10^5$ K. The mass accretion rate associated with the HeII luminosity using the semiempirical estimates of Patterson and Raymond (1985) for a white dwarf accretor is $8 \times 10^{-10}$ gr/s, which compares well with the lower limit obtained from the UV continuum luminosity, $L(\text{UV}) \approx 3 \times 10^{32}$ ergs/s. Additional arguments in favour of a white dwarf accretor are, for example, the presence of broad wings in the Sill 1892 and CII 1909 A emission lines seen in the IUE high resolution spectra, and the presence of flickering in the optical (Walker 1977; Bianchini and Middleditch 1976). Different views on both RS Oph and T CrB can be found in Webbink et al. (1987) and Livio, Truran and Webbink (1986).

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Friedjung, M. 1988, preprint


We exemplify how white dwarf research has profited during the first ten years of IUE. We discuss especially hot DA stars, calibration problems in the UV range, the 1400/1600 Å quasimolecular features in cool spectra, the helium-rich DB and DBa stars, cooler non-DA stars with UV carbon lines of type C and metal lines of type DZ. A re-examination shows that carbon abundances are only weakly dependent on T(eff). For dredge-up this implies helium-layers of different thickness.

Finally we mention hot white dwarfs with metal lines, especially the PG 1159 class.

Keywords: White dwarfs; spectral types, IUE calibration. Atmospheres: carbon abundances, metal abundances.

Introduction

During the last decade the field of white dwarf research has been enormously expanded, due to the combined effects of new surveys, increased telescope power, modern detection techniques and last not least, observations from space. IUE has been the most important single instrument in this respect.

Since the field has been covered extensively in the recent volume "Exploring the Universe with the IUE Satellite" by the excellent review of Vauclair and Liebert (Ref.1) and since there is little to add or to update this during the last two years, I shall not try to repeat it, but instead restrict this lecture to a somewhat more historical approach which emphasizes those results which are essentially due to IUE observation. I feel this to be fitting for a "Celebratory Symposium", in which I shall show - as I hope to pleasure of the wider audience - some of the most interesting and beautiful IUE white dwarf spectra obtained during the last ten years.

I will not go into details especially since these have been dealt with in lectures given at recent meetings, like the last European Workshop on White Dwarfs (Ref.2) or the Second Conference on Faint Blue Stars in Tucson - the proceedings of which just appeared (Ref.3) or the IAU Symposium on Planetary Nebulae in Mexico City (Ref.4).

There is also no time to discuss the most interesting evolutionary connections to central stars of planetary nebulae and other pre-white dwarf stages - again I refer to Ref.3 and 4, and in addition to the extensive survey by Sion (Ref.5).

Finally, I omit reference to white dwarfs in binaries, like cataclysmic variables or AM Herculis stars, although IUE observations have been extremely successful in this field.

Instead I shall consider the basic varieties of single white dwarfs of different spectral classes. It is well known that the majority of degenerates cooling through the white dwarf region are of spectral type DA, showing only hydrogen lines, and having in general almost pure hydrogen atmospheres. They are observed in the effective temperature range of about 70000 to 55000 K with the variable ZZ Ceti stars occurring between 12000 and 10000 K.

By contrast about 20 % of the white dwarfs have hydrogen-free atmospheres and appear predominantly as DB stars, with He I lines, above 11000 K, or below this temperature (where He I lines cannot be excited) as either DC stars (with continuous spectra only), DQ stars which are so classified for the presence of CO or CI lines, or DZ stars, so called if they show - rarely - metal lines.

As observations have been refined, more and more trace elements have been detected. I present here a survey, from the recent lecture by Fontaine and Wesemael (Ref. 6) - which also indicates possible mechanisms which operate on white dwarf surfaces. Since one of the IUE achievements during the last decade was the detection of strong carbon features in most cool non-DA stars, and since we were especially involved with the first observations made at VISSPA, one may forgive me if I spend a larger fraction of my time on a discussion (under Sect. 2.2.) of the corresponding results. Fig.17, below, drawn to summarize the present carbon situation, and a few remarks concerning its interpretation, aside from a new IUE observation of a DBA star (Sec. 2.2.1.) are original contributions to this lecture.
1. DA Stars

1.1. Hot DA white dwarfs and IUE flux calibration

The first IUE observations were made by Greenstein and Oke (Ref. 7) which demonstrated that the UV flux distribution for DA stars is rather smooth with Lyman-α as the only recognizable line feature. This was in agreement with predictions from model calculations for metal-free hydrogen-rich atmospheres.

Flux distributions for DA white dwarfs were thus recommended for IUE calibration purposes. During the years this method has been applied and improved. Finley, Basri and Bowyer (Ref. 8) analysed more than twenty DA stars with temperatures between 20000 and 70000 K and proposed correction curves for IUE spectra as a function of the époque (up to 1982.5) which amounted to an average increase of F(λ) of 10%, between 1300 and 3100 Å. However the predicted fluxes used for the comparison were obtained from observed V magnitudes and optically determined temperatures, and the corrections were not extended below 1350 Å, due to the uncertainties in the calculation of the Lyman-α wings. Recently this method has been applied and considerably improved by the excellent small aperture SWP observations of Holberg, Wesemael and Basile (Ref. 9). The main advantage of using small aperture spectra is the nearly complete elimination of the geocoronal Lyman-α emission component. Fig. 1 demonstrates the high quality of these spectra, from which it was possible to derive more accurate effective temperatures and surface gravities for hot DA's (above 30000 K).

Fig. 1. Lyman-α profiles of hot DA white dwarfs obtained with small aperture SWP exposures by Holberg et al. (Ref.9)

The derived average surface gravity, log g = 7.96, agrees well with that obtained for the majority of the cooler DA stars, for which Weidemann and Koester (Ref.10) found log g = 8.02 by evaluation of optical multichannel data for 70 DA stars in the most g-sensitive region of T(eff) between 8000 and 16000 K, using the calibration of Hayes and Latham (Ref.11) whereas they obtain log g = 8.09 for the calibration AB 79 of Oke and Gunn (Ref.12). The IUE results for the hot DA's thus fill a gap in a temperature region for which the optical results (see Ref.13) were more and more unreliable. The slightly lower average surface gravity, however, does not imply smaller average masses, since recent evolutionary calculations all the way from the asymptotic giant branch (AGB) through the central star of planetary nebulae phase down the white dwarf cooling track (Ref.14) demonstrate that the radius of zero-temperature degenerate configurations is only slowly reached.

Fig.2. Evolution of 0.6 M☉ star. Log cooling age marked

Fig.3. g-correction from Fig.2, (1) H, (2) He surfaces.
The mass-radius-(surface gravity) relation of Hamada and Salpeter (Ref. 15) must thus be corrected for hotter white dwarfs, a fact which is important for mass determinations. Holberg et al. (Ref. 9) do indeed find a tendency for the hottest stars to have the lowest gravities, i.e., a confirmation of the fact that most DA stars fall into a narrow mass range around 0.6 $M_\odot$. HZ 43, however, seems to be an exception, with higher mass. It is exceptional also in the surface ratio of hydrogen to helium, which otherwise seems to be correlated with $T(\text{eff})$. EUV observations with Einstein, Ref. 16a, EXOSAT observations, Ref. 16b, general discussion: Ref. 16c). As for the IUE calibration, the Holberg et al. results demonstrate that in the range $\lambda$ = 1200 - 1300 Å observed fluxes which were calibrated according to Bohlin and Holm, 1980 (Ref. 17) should be lowered, thereby decreasing the slope and estimated temperatures, see Fig. 4. This fact is corroborated by IUE observations and recent analysis of the hot (non-DA) white dwarf KPD 0005+5106 (Ref. 18, especially Fig. 6) which has a most probable temperature of 80000 K but a slope below 1400 Å which seems to be indicative of more than 100000 K (see also 2.1).

These problems have very recently been restudied by Finley et al. which used continuum flux distributions and model atmospheres for hot DAs with temperatures from Holberg et al. (see their contribution at this Meeting) in order to get better calibration corrections. Holberg et al. have also extended their investigations and discuss implications for diffusion theory and photospheric stratification (contributed paper at this Meeting).

1.2 Cool DA stars, ZZ Ceti variables

IUE SWP low dispersion spectra and high dispersion spectra of 40 Eri B revealed the existence of an unknown absorption feature at approximately 1400 Å which was for some time considered to be a metallic line (Ref. 19 - 21). (Fig. 5).

This and another absorption feature at 1600 Å was found in several more DA SWP spectra. (Ref. 22 - 24). (Fig. 6)

The mystery was finally resolved when, independently, the European group (Koester, Weidemann, Zeidler and Vaucclair, Ref. 24) and the American group (Nelan and Wegner, Ref. 25) identified these features as due to quasi-molecular absorption of $H_2$ (1600 Å) resp. $H_3^+$ (1400 Å) molecules formed in the far extended Lyman-α wing. The features are strongly temperature dependent.
(see Fig.7, from Ref.24) and thus provide the possibility of better temperature determinations for DA stars between 10,000 and about 17,000 K.

Fig.7. Theoretical temperature dependence of 1400/1600 Å features for DA model atmospheres (Ref.24).

Into the lower range fall the variable, non-radially pulsating ZZ Ceti stars, for which temperature determinations are especially important in order to provide the theoreticians with the limits of the instability strip.

Whereas Greenstein (Ref.26) found the red and blue edges to be at 10,600 resp. 12,000 K (on the AB 79 calibration), Weidemann and Koester (Ref.10) obtained an effective temperature range from 11,200 to 12,500 K (on the Hayes-Latham calibration from multichannel data) and a very narrow mass range. The Canadians (Wesemael, Lamontagne and Fontaine), have used IUE spectra and the 1400/1600 Å features in an attempt of improvement. Fig.8 (right side) shows the spectra for 7 variable DA stars (Ref.27).

Fig.9. Optimal fits of model flux distributions to SWP spectrum of G226-29. Top: Nelan/Wegner grid (Ref.25), T(\text{eff})=11,760; bottom: Koester models (Ref.24), T(\text{eff})=12,390 K.

The evaluation results in a ZZ Ceti temperature range from 11,400 to 13,000 K, however the exact location depends on the model grid which predicts somewhat different results as shown in Fig.9 (left side) and Table 2 in Ref.27. If the results are thus not yet completely satisfactory, the 1400-1600 Å case has at least demonstrated how IUE observations have provided completely unexpected new information and a valuable tool for better analysis of these common DA stars.
2. Non-DA stars

2.1 DB stars

White dwarfs with helium-rich atmospheres indicated by the appearance of HeI and no hydrogen lines are classified DB and are found in the temperature range from 12000 to about 30000 K. Since their space density is about five times lower than that of DAs in the same temperature range, and since they are strangely absent between 30000 and 45000 K (Ref.28), there are not too many bright enough to be accessible with IUE. An extensive study based on IUE low resolution observations has recently been published by Liebert et al. (Ref.29), with special emphasis on the hotter objects (above 18000 K) between which there are four pulsating variables. V magnitudes are between 14 and 16, accordingly the quality of the (mainly SWP) spectra is sometimes low as seen in Fig.10 which presents binned fluxes only.

The brightest star and most interesting case is GD 358 which is at the same time a pulsating variable. Its temperature - important for the location of the instability strip - has been a matter of debate. The IUE slope in the SWP range favors 28000 ± 2000 K (Ref.30), 27000 ± 2000 K (Ref.29), whereas the analysis especially of multichannel data and high quality line spectra with model atmospheres yields 24000 ± 1000 K (Ref.31) as seen in Fig.11.

![Fig.11. Observed and calculated energy distribution for the DB star GD 358. MCSP: multichannel spectroscopy (Ref.31).](image)

The reason for the discrepancy is at least partly the above-mentioned calibration problem in the SWP range. GD 358 has recently been observed with IUE as the first DB with high resolution by Sion et al., results are presented at this Meeting.

Another recent publication covers predominantly the cooler DB range. Wegner and Nelan (Ref.32) have evaluated optical and IUE data for a total of 27 DB stars out of which 15 have been accessible to IUE. The UV spectra are generally featureless but could be used to determine better temperatures and to put upper limits on carbon abundances (see below 2.2).

DB white dwarfs seem to have about the same average mass as the DA stars, 0.55 M_☉ (Ref.33), but it is still not established if they are coming from pre-white dwarfs which have already lost their hydrogen-rich surfaces or get their spectral appearance due to surface evolution during the white dwarf cooling stage itself (see below).

Since there is evidence for both possibilities it may be that the DB stars are in reality a mixture of stars with different origin.
2.1.1 DBA-stars

Whereas normal DB stars do not show any lines other than helium, there are some objects in which faint Balmer lines have been detected, they are classified DBA. A recent list by Shipman et al. (Ref.34) of 33 spectroscopically surveyed DB white dwarfs from the Palomar-Green sample identifies five new DBA stars.

The hydrogen abundances must be of the order of \(10^{-4}\). It is of interest to check on the visibility of Lyman-\(\alpha\) in these stars, unfortunately only one object, G 200-39, is bright enough \((V = 15.14\text{, }14500\text{ K})\) to be accessible with IUE. However, in order to have the weak Lyman-\(\alpha\) line not filled by geocoronal emission, one has to use the small aperture. This has now been done: the SWP low resolution, small aperture image, recently obtained with 350 min exposure, does indeed clearly show the Lyman-\(\alpha\) wing! (Fig.12).

In the case of GD 323 however, it has been demonstrated by Jordan and Koester (Ref.38) that it is not possible to reconcile the observations with any kind of stable stratified atmosphere.

Liebert now feels that GD 323 - at the 30000 K upper limit of the DB range – may be one of the rare cases which is caught in the unstable state of transition (Ref.39).

However, in order to explain the hydrogen abundances in DBA stars by convective mixing, one needs more H, of the order of \(10^{-10}\) \(\text{M}_\odot\) rather than \(10^{-14}\) \(\text{M}_\odot\), and accretion seems another possibility, against which there is other evidence, e.g. in GD 40, (below). These problems have thus not yet been solved. (See Refs.37, 61) for recent surveys.

2.1.2 The DBZ star GD 40

A most interesting exception to the general absence of metal lines in DB stars is GD 40 (GR 304, WD 0300-013 in the McCook/Sion Catalogue, Ref.40), which had first been noticed due to the appearance of strong Ca II lines in the visible. The following UV observations revealed strong iron and magnesium and possible silicon features in the LWR range, the detection of which constituted quite a milestone in IUE observations of white dwarfs (Ref.41).

At \(V=15.5\), and \((\text{eff}=14000\text{ K})\) a SWP spectrum was difficult to obtain: it should have revealed more Si and possible carbon lines. The SWP spectrum was finally observed by Shipman (Ref.42) but did not show any convincing features. However it allowed to establish upper limits of \(2-10^{-7}\) to the atmospheric abundances of Si/He and C/He. According to the new classification scheme for white dwarfs (Ref.43) the appearance of metal lines in cooler white dwarf spectra is indicated by the letter Z, and GD 40 is thus classified DBZ. Another DBZ star, CBS 78, with even stronger Ca II lines in the visible, has recently been discovered, but is unfortunately too faint \((17.\text{ mag})\) to be observable with IUE (Ref.44).
2.2 Cooler non-DA stars, of spectral type DQ,DZ,DC

2.2.1 DQ stars

A real and unexpected breakthrough achieved by IUE observations was the discovery of strong CI absorption lines in the spectra of non-DA stars with temperatures below the DB range, i.e. below 12000 K. Before that discovery most cooler non-DA stars were classified DC - indicating continuous spectra with no lines at all in the visible region. An exceptional, smaller group, however, showed C₂ absorption bands of variable strength, especially at 4670 Å, and were accordingly classified \( \lambda 4670 \) or \( C₂ \) stars.

When the first C₂ star, L 145-141, was observed at VILSPA in 1979, the SWP spectrum appeared strikingly depressed, with such broad absorption features (see Fig.16) that at first C₂ molecular dissociation appeared the most plausible explanation. (Ref.45,46)

![Fig.16. Comparison of 4 IUE spectra with strong CI absorption lines, demonstrating asymmetry of \( \lambda 1930 \) line. (Ref.49)](image)

However, when the next object, L97-3, with much fainter - if any - visible C₂, (Fig.14) was observed (Ref.47) it turned out that the features discovered were indeed the very strong CI lines (Fig.15) which had been predicted by Bues (Ref.48) from model calculations. The spectrum of L97-3 as analyzed in Kiel (Ref.47) could be explained with unexpectedly low atmospheric carbon abundances, of the order of C/He=10⁻⁶, however the nonresonant 1930 Å line appeared to weak compared to the observation. The fact that this line is much stronger than predicted is also partly responsible for the first misinterpretation of L145-141.

Zeidler-K.T. in her thesis (Ref.49) has demonstrated that a dissociation continuum - although present - is too wide to be responsible for the unusual shape of \( \lambda 1930 \), which was confirmed in further observations of the DC white dwarf G33-49 (Ref.50) see Fig.16. At the same time Wegner (Ref.51) had obtained IUE spectra for the DC star LDS 678B, and clearly identified the UV CI lines. Another C₂ star, with strong visible C₂ bands, L 879-14 was only accessible in the LWR range but showed a predicted CI line at 2480 Å.

The presence of CI UV-lines was subsequently (Refs.52 - 55) confirmed for nearly all non-DA white dwarfs between 10000 and 6500 K, independent of their former classification, which was accordingly changed to DQ - indicating carbon in the new classification scheme (Ref.43).
Analysis has been performed and carbon abundances have been derived for most of them, based on optical and IUE data wherever possible (Ref.56,57). Typical abundances turned out to be C/He = 10^{-5} to 10^{-7}, however, inclusion of optical data, for stars too faint for IUE, indicated cases with even higher carbon abundances (Ref.58), like 3·10^{-3} in the case of G 227-5. The distribution over effective temperature showed a broad maximum at 1000 K, and attempts have been made to explain this by convective dredge-up of diffused carbon on top of the interior He/C interface (Ref.56,59). If this interpretation were correct, the beautiful UV CI lines would directly confirm our theoretical prediction that stellar evolution leads to carbon/oxygen cores for low and intermediate mass stars! However some doubts remain, since the correlation of C abundances with T(eff) is evidently not as strong as first presumed.

Especially the predicted turn-down for T(eff) > 10000 K is badly documented. I show a collection of all data, including the recent observations of cool DB stars (Ref.32) in Fig.17.

If the dredge-up hypothesis is correct, it means that the depth of the carbon core surface, or equivalently the thickness of the helium-mantle must also be different from star to star. It has indeed been shown by calculations of the Canadian group (Ref.60) that dredge-up would not occur, if the helium layer had the thickness of about 0.01 M which is predicted from pre-white dwarf calculations. Accretion has thus been discussed as an alternative possibility for the explanation of carbon in DQ atmospheres, and although it cannot be ruled out, the non-accretion of hydrogen, the relatively high carbon abundances in some cases, and the absence of oxygen (Ref.56) at least in the cooler DQs make this hypothesis very improbable.

The problem of outer layering of hydrogen and helium is indeed complex and at the moment widely unsolved. For details I refer to recent papers presented at the Tucson Conference on Faint Blue Stars, Ref.6,61,62.

As demonstrated, IUE observations have been extremely helpful in establishing constraints, unfortunately further observation of non-DA stars will be very time consuming, since the few remaining stars need full shift exposure time.

2.2.2 DZ stars

As optical observations improved it turned out that several of the cooler non-DA stars, formerly classified DC, showed CI absorption (or in some cases faint hydrogen lines). Stars with CII lines were formerly classified DF, but according to the new classification scheme adopted (Ref.43), the appearance of any metal lines in spectra of cooler white dwarfs is indicated by the letter Z (e.g. DZ, DB2, DAZ, DQZ...).

IUE has contributed new information and really opened up this field for extensive study. The first observations revealing strong metal features of Mg, Fe and Si in the LWR region of Ross 640 were obtained by Greenstein and Oke 10 years ago and analyzed with the help of synthetic spectra by Cottrell and Greenstein (Ref.63).

It is striking that the result of GD 40 (see above) is confirmed in nearly all DC cases: only upper limits can be established which are of the order of C/He ~ 10^{-7}. On the other hand we see in the cooler, below-DB range that the carbon abundances vary considerably, and that the single sequence suggested by former diagrams (Ref.55,59) does not exist.
Fig. 18 shows the beautiful result for this 8800 K, 14 mag, DZa star. The second case, GD 40, a 15.6 mag DB2 star, has been discussed already under 2.1.2 above. The third object, L 745-46 A, a former Fe at 7800 K, could also be observed in the SWP range and revealed the presence of CI. In the LWR range appear Mg, Si and possible Fe features. The star has been analyzed in Kiel with the result shown in Fig. 19 (Ref. 64).

Fig. 19. Best fit to LWR spectrum of the DZa star L745-46A (Ref. 64)

The fourth and last star of this category observed by IUE is L 119-34, at 14.4 mag and at somewhat higher effective temperature, above 9000 K, it was recently also possible to secure a full-shift but still very noisy and somewhat underexposed SWP spectrum, which clearly shows the CI lines expected already from the LWR range and the general findings for cool non-DA stars in this temperature range.

Fig. 20 shows a best fit to the LWR spectrum from a model with Mg/He = 2 x 10^-9, Fe/He = 8 x 10^-10 and Si/He = 6 x 10^-10, (with adjusted broadening parameters for the Mg lines, see Ref. 64 for a more detailed discussion of this unsolved problem). A preliminary analysis of the SWP spectrum yields a carbon abundance of 5 x 10^-7 (Ref. 65).

Again some further DZ stars are unfortunately too faint for IUE observations, which are advantageous compared to optical observations for the detection of metals (especially in the hotter range) as demonstrated in Fig. 21 (Ref. 64).

Fig. 21. Lower abundance limits for the visibility of the strongest metal lines (12000K model, Ref. 64)

Synthetic DZ spectra have recently been calculated for a wide range of metal, C and H abundances in Kiel (Ref. 66).

In order to explain the presence of these trace metals in cooler white dwarf atmospheres and the wide range of abundances at a given temperature - as shown in Fig. 22 (Ref. 64), accretion by intermittent passage of these slowly cooling white dwarfs through interstellar clouds has been proposed (Ref. 67 - 69). However, up to now model calculations of diffusion under a variety of assumptions have not yet yielded convincing results. For further discussion I refer to Ref. 61.

If one considers the expected visibility limits as plotted in Fig. 22 one notices that trace metals could as well be present in comparable amounts in the atmospheres of hotter non-DA stars, but remain invisible.

Fig. 22. Abundances for DQ and DZ stars (Ref. 64)

Detection limits for H, C, N and O lines in helium-rich white dwarf atmospheres as a function of T_eff (after Stumkat, 1983, and KWZ) compared to observed abundances.

Detection limits for Ca, Mg, Si, Fe in helium-rich white dwarf atmospheres and derived metal abundances for DZ stars and GD40 (this paper, Table 2). Solar abundances and symbol identification at right scale.

Again some further DZ stars are unfortunately too faint for IUE observations, which are advantageous compared to optical observations for the detection of metals (especially in the hotter range) as demonstrated in Fig. 21 (Ref. 64).
3. Metals in IUE spectra of hot white dwarfs

Although I cannot go into details in this short review I must in closing at least mention the striking discovery of non-interstellar C, N, O and Si lines in IUE high resolution spectra of a variety of hot DA and non-DA stars, detected first and extensively discussed by Bruhweiler and Kondo (Ref.70) and later by Wesemael, Henry and Shipman (Ref.71) or Sion, Liebert and Wesemael (Ref.72). The lines originate either in the photosphere or in circumstellar material and are interpreted by an interplay of selective radiative support, gravitational settling and/or mass loss. The problems involved are not yet solved, however it appears that at least in the case of Feige 24 and Wolf 1346 (the comparatively coolest of these stars) the presence of Si can be explained by the existence of radiatively supported silicon clouds (Ref.73).

For a more detailed discussion I refer to Vauclair and Liebert (Ref.1), the review lecture presented by Shipman at the Tucson conference 1987 (Ref.74) and a forthcoming paper by the Canadian research group (see Ref.75).

In this context I finally mention the highly ionized metal lines which have been found in the very hot PG 1159 (GW Vir) class stars besides the C IV λ 1550 line which is found in many of the hottest DA0 or DO(= He II) white dwarfs (Ref.76). The analysis of the PG 1159 stars and of the even hotter object H1504+65 (Ref.77) is not yet completed. These objects are of special interest for the question of evolution from the pre-white dwarfs (AGB and planetary nebula) stages into the white dwarf region (Ref.1, 5, 78).

It thus seems appropriate to close this survey about the beautiful IUE achievements in the white dwarf field during 10 years of operation with a reproduction of the informative SWP spectra of three PG 1159 stars (Ref.76) in Fig.23.

Fig.23. IUE SWP spectra of three stars of the PG 1159 class, the hottest white dwarfs observed. (Ref.76)

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IUE OBSERVATIONS OF PULSATING STARS: ATMOSPHERIC STRUCTURE, SHOCK WAVES, AND STELLAR WINDS

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ABSTRACT

Classes of pulsating stars studied by IUE include Miras and semi-regular stars, Cepheids (Classical and Population II), RR Lyrae stars, Ap/Swirl stars, A Scuti stars, B photospheric stars, hot subdwarfs (W UMa stars), and pulsating white dwarfs. In the Section 1 of this review, existing IUE observations are briefly surveyed by type of variable star. Section 2 concerns current theoretical understanding of properties of the atmospheres of pulsating variables stars modeled relevant to the interpretation of IUE observations: in Section 3, IUE data for long period variables (Miras and semi-regular stars), Classical Cepheids, and Ap/Swirl stars are compared with what is expected on the basis of theoretical atmospheric models.

Keywords: Pulsating stars, stellar atmospheres, shock waves, stellar winds, and mass loss.

1. CLASSES OF PULSATING VARIABLE STARS OBSERVED WITH IUE -- EVOLUTIONARY STATUS, AND SOME PROBLEMS

Radially pulsating stars are found in the classical Cepheid instability strip, the cool (Mir) pulsation strip, and the hot B Cep (or A Scuti) instability region (Figure 1). For the Cepheids and related yellow variables, the pulsation is driven by the combination of a Sun-like mechanism in the HeII -> HeI ionization zone (e.g. J. J. Cox 1980). For the Miras, the pulsation is similarly driven in the combined HeII -> HeI, HeI -> HeII ionization zone; the driving is complicated by the fact that this region is convective (Wood 1982, Oestle and Cox 1986). For the B Cep stars the pulsation mechanism is not yet certain, although there are some indications that resonances between convective modes and pulsation modes in the presence of rotation can account for the radial pulsation B Cep variables and the non-radially pulsating B Per stars and B Per variables (see for example Smith 1989).

The Classical Cepheid variables are Population II stars with masses between 1.5 M$_\odot$ and 15 M$_\odot$, crossing the instability strip either in transit from the main sequence to the red giant region or more likely, because the evolution is slower during the blueward loop, populated with core He burning. The uncertainty in the lower mass limit is due to the persistence lack of agreement between the masses derived from the pulsation behavior (Period-Mass-Radius relations, period ratio in beat Cepheids, bump positions in Cepheids with periods near 10 days) and the evolutionary masses (relating the luminosity of the Cepheid to the mass of the star as it begins Cepheid pulsation). IUE studies of main sequence companions of Cepheids have provided important constraints on the luminosities and masses of the Cepheids, as recently reviewed by Bohm-Vitense and Querci (1987). The use of IUE to determine atmospheric properties of Cepheids, as discussed by Bohm-Vitense and Querci, is also reviewed in detail in Section 3 below.

The A Scuti stars are also Population II variables in the Cepheid instability strip: they are ~2 M$_\odot$, late A or early F stars on or near the main sequence. IUE studies of these stars have emphasized the atmospheric properties, specifically the search for "chromospheric" emission (Fracassi and Pasinetti 1982; Fracassi et al. 1983, 1988). A recent suggestion by Willson, Brown and Strick-Marcell (1987) that this pulsation, combined with rotation, could lead to mass loss, of evolutionary significance, is also being investigated by IUE through new observations of Pleiades A stars combined with detailed studies of the archival spectra of rapidly rotating field A and F stars (Willson and Brown, in prep.).

The Population II variables in the Cepheid instability strip include the W Vir variables ("Pop. II Cepheids"), RR Lyrae variables, BL Her stars, RV Tauri variables, BX Peg stars and Anomalous Cepheids. Comparison with evolutionary calculations suggest that the W Vir variables and the RV Tauri stars are probably ~1 M$_\odot$ stars making blue loops through the Cepheid instability strip (Harris 1983): the RR Lyrae stars are horizontal branch (core-H burning) stars with masses ~0.6 M$_\odot$ (Iben and Rood 1970); the BL Her stars are post-horizontal branch stars with masses ~0.6 M$_\odot$ (Bodenhuber et al. 1980; Carson and Stothers 1982); the BX Peg variables are pulsating blue stragglers, stars with masses somewhat greater than one solar mass on or near the main sequence (Proffit 1983); and the Anomalous Cepheids are evolved blue stragglers, with masses ~1.5-2.0 M$_\odot$ (Cox and Proffit 1988). Bohm-Vitense, Proffit and Windstein (1987) observed two W Vir stars directly after maximum light and attempted to fit a static atmospheric model to them, but encountered some difficulty getting a consistent set of parameters to fit. Further study is necessary.
(1964) found strong null emission in H β on two occasions (declining light and near minimum) but no emission for H ν on two separate occasions. They noted that this behavior was greatest when the line was near maximum light. They ruled that this behavior was inconsistent with the general trend of the red giant variables, as shown by Capacci and Castelli (1962) and Hiltner, to study the line emission as well as the continuum emission in these H β lines. Smith and Willson (1967) obtained spectra of two RR Lyrae stars and found them to increase the effective temperatures and abundance determinations; they also noted possible circumstellar absorption, and shock emission of one phase.

Among the red giants and supergiants are found a variety of types of long period variables. The relatively rare, large-amplitude, radial pulsations of variable stars are associated with giant branch stars (shell II burning stars with shell flashes) and represent the last red giant stage before the formation of a planetary nebula for stars around 1-2 M ☉ (Willson 1962; Wood 1967; Willson 1969). The closely related RR Lyrae sources differ from the Miras by having systematically longer periods and higher mass loss rates. This class probably includes both pseudostellar mass stars that have lost most of their envelope masses and stars with higher envelope masses, up to 3 M ☉. While direct observations of the properties of RR Lyrae Miras are too uncertain to allow for the direct determination of the pulsation mode, studies of the shock waves in Miras strongly support the view that they are fundamental-mode pulsators (Willson 1967; Hansen 1968). Many red giants are semi-regular (S.R.) variables; long-period variables that differ from the Miras in the amplitude of their pulsation (S.R.), in the regularity of their pulsation (S.R.), in their luminosity class, in their spectral type (S.R.), in their magnetic field (S.R.), and in other properties (S.R.). The mechanism governing the variable of these classes of variables have not yet been clearly identified, but may include chaotic radial pulsations (Bode 1987), multiple radial pulsation modes, non-radial pulsations, giant convection cells (Taylor and Williams 1975), or magnetic activity. Some of the S.R. variables show Mira-like pulsations, but with smaller visual amplitude and often shorter periods; this group includes many carbon stars. The use of Hα observations to probe the atmospheric structure of Miras and S.R. variables is discussed in Section 3.

Across the top of the HR diagram there are a variety of pulsating stars, most of which also show evidence for substantial mass loss. The prototype mass losing star P Cyg has been studied with IR by Tapia et al. (1977), and by Stark (1981); Loomis et al. (1986) and Becklin and Neugebauer (1975); and Neugebauer et al. (1973) observed the middle-Sandage variables to 50 and 60%. The RR Lyrae variables, whose most obvious variability appears to be the result of the formation and ejection of discrete cool clouds, also pulsate, possibly because they lie in the extension of the extended instability strip to higher luminosities (Stonich and Minniti 1983, 1985; Neugebauer et al. 1985). Hiltner et al. have shown that these stars have hot "chromospheres" both during and between episodes of heavy dust obscuration (Laws et al. 1986; Hiltner et al. 1974, 1981; Ely et al. 1977; Hiltner et al. 1984; Hiltner 1985).

The two ionization-driven pulsation instability strips extend into the white dwarfs: the He + H instability drives the evolution of the non-DA white dwarfs, while the H + H instability drives, the evolution of the DA white dwarfs (Waelkens 1986). Tidman et al. (1986) and Howert et al. (1980) have used Hα observations to improve the effective temperature determinations for the pulsating DA white dwarfs. Hiltner et al. (1984) also used Hα to study the pulsating white dwarf ZZ Leo; they were able to show that the variations in the Hα spectrum with phase at the right curve.
corresponded to a temperature variation in phase with the light variation, and thus is consistent with the interpretation of the oscillations as high-order harmonics.

Among the U stars, there are both radially pulsating (R Cap) and non-radially pulsating (the 82 Her) variables. For the 82 stars, there have been many IUE investigations; the reader is referred to the recent review by Snow and Stalio (1991) for a discussion of this topic. The interpretation of IUE observations for the 82 stars is also discussed in Section 2 below.

IUE observations of the hot subdwarfs, including the pulsating PG1159 (= GW Vir) stars, were included in the review by Vauclair and Liebert (1987). IUE observations have contributed to the determination of the effective and atmospheric temperatures for these objects (Land et al., 1984).

2. PROPERTIES OF THE ATMOSPHERES OF PULSATING STARS AND THE INTERINTERACTION OF IUE OBSERVATIONS

Stellar pulsation produces a number of modifications in the atmospheric parameters: shock waves form and dissipate mechanical energy, density gradients decrease and thus the local density increases, temperatures may increase due to heating by shocks or may decrease due to adiabatic expansion, and mass loss often results. In this section I will emphasize these results of the theoretical studies:

1. The structure (H(R), H(R), T(R)) of the atmosphere of a pulsating star is always very different from its stellar structure. (2) The structure depends most strongly on the period (or more specifically, on Q = M/L) and very weakly on other stellar parameters. (3) The structure is affected by the action of a wind-driving mechanism, such as radiation pressure; the efficiency of such mechanisms is affected by the presence of pulsation, so that both M and the atmospheric structure result from a complex interplay between pulsation and other processes.

The atmosphere of a pulsating star can be roughly divided into up to four regions, as defined by Willson and Bowen (1984): (1) In the lowest region, the undulationsphere, the dominant motion is a standing wave pattern without strong shocks or instabilities. (2) In the undulationsphere, there are strong shocks that are effectively isothermal. A radiolosphere is a region in which the temperature drops below the radiative equilibrium temperature at all times; a radiolosphere may form where the shocks become effectively adiabatic. Finally, the wind is conventionally defined as the superwind outflow beyond the "Parker point" (Willson and Bowen 1985, 1986 and 1988).

The location of the boundary between the undulationsphere and the radiolosphere (r1) relative to the photosphere (r0) is the radial position where shocks form, determined how easy it will be to observe the shocks. Atmospheric models available to date have been calculated using a "moving piston" inner boundary condition (Hill 1972, 1973; Hill and Willson 1979; Willson and Hill 1979; Wood 1979; Bowen 1982). In such models, the position of r0 depends on the depth of the proton below the photosphere and on the magnitude of the motion of the piston. The relationship between the position of r0 and the velocity of the piston is given by the condition that the internal damping plus the atmospheric damping must equal the internal driving. Nonlinear hydrodynamic models for the interiors of pulsating stars have not included the atmosphere in damping. However, according to the atmospheric models, the atmospheric damping can be substantial; that is not included in internal pulsation calculations.

In Figure 2, the motion of "travelling particles" or model shells in a Mira model computed by Bowen are shown for the region nearest the photosphere. The dark line is the position of the photosphere. This model has been driven by a piston amplitude such that r1 = R. The region below the photosphere in this case is clearly moving in a standing wave pattern. Above r1, there are travelling shock waves: a temporary "precursor" shock followed by the "main shock". Whether or not real Miras will have precursor shocks depends on two factors: (1) whether the assumed sinusoidal piston motion is actually a good approximation to the true motion at this depth, and (2) whether, when the effects of radiative transfer and convective transport are included below the photosphere, the motions will be similar to those shown here. Further
An analytic description of the atmosphere was introduced by Willson and developed by Willson and Owen (1980); Willson and Hill (1979); Willson and Owen (1980a, 1980b). In this region, the material is in free fall most of the time; the shock waves propagate upward at speeds well above escape, and typically survive for several years, although they may not be observable that long. If the velocity amplitude of the shock waves, \( v_{sh} \), depends on the local pulsation period (\( T_p \)), \( \dot{m}(r/b)^{1/2} \) and \( v_{esc} \) and only weakly on other parameters, such as the speed of sound at the static scale height \( H \), the local scale height typically greatly exceeds the static scale height. In the ballistic limit, where the material is given an outward velocity \( v_o \), \( v_{sh} \) by a shock moving in response to gravity alone during the rest of the period, \( v_{sh} \) depends only on \( T_p \) (Figure 1). The radial excursion of the material during each cycle, \( T_p \), is also a function of \( T_p \) only by the ballistic limit, and is large for the \( T_p \) values typical of radial pulsation (\( 10^4 \) yr). The inclusion of the effects of pressure gradients decreases \( \dot{m}(r/b)^{1/2} \), but often not by very much. Thus in the presence of pulsation, shocks form where these shocks are effectively isothermal, there is a greatly increased scale height; in this region, the motion is mostly ballistic, and \( v_{sh} \), \( \dot{m} \) and \( v_{esc} \) all depend primarily on \( T_p \).

Figure 1. Shock amplitude \( \delta v \) and \( r \) in \( r < r_{sh} \), where \( r \) is the vertical extent of the trajectory, \( v_{sh} \) for strictly perfect, ballistic motion, this is an upper limit to the shock amplitude and trajectory height in more realistic models.

Whether or not a pulsating star will form in the atmosphere of a pulsating star depends on whether the density is high enough to produce shocks at densities above the critical adiabatic density, or whether \( r < r_{sh} \) and \( \delta v > v_{sh} \). Whether we will see into the undisturbed depends on \( r \), \( v_{sh} \), and \( v_{esc} \). Thus we can characterize the atmospheres of variable stars by noting the presence or absence of each of these regions: \( L, A, C \) or \( W \). As the amplitude of pulsation increases, the atmospheric configuration is expected to develop from \( L, A, C, W \) to \( L, A, W \) to \( L, A, W, C \) to \( L, A, W, C, W \). By the amplitude of pulsation, the atmosphere is more likely to give rise to the formation of a massive wind, and at the same time, the density is likely to be the result of non-equilibrium processes, for example, in the material emerging from the passage of a shock front.

In modeling the atmospheres of pulsating variables, it is essential to include the region where the wind develops. This means in practice that the modeling must include regions of the atmosphere where the density is quite low, and where in consequence the actual atmosphere is the result of non-equilibrium processes. The inclusion of such effects is important in two ways: first, it affects the structure of the atmosphere; second, the observed emission is likely to be the result of non-equilibrium processes, for example, in the material emerging from the passage of a shock front.
Figure 4. From Bowen 1988. 4a (left): Standard Mira model (T = 3800K, P = 350$^2$, M = 1.2 $M_\odot$, R = 270 $R_\odot$) including the effects of radiation pressure on dust, assumed to condense where the radiative equilibrium temperature is 1500K.
4b (right): Standard Mira model but without the effects of dust. Heavy, light lines display the velocity, density, and temperature structure at two phases, half a cycle apart. The two major effects of dust are clear: it drives a more substantial wind, and the resulting adiabatic expansion of the atmosphere lowers the temperature.
For pulsating stars, as for non-pulsating stars, IUE observations can be used to improve our knowledge of their fundamental properties. IUE observations have led to improved estimates for the effective temperatures and luminosities of the pulsating white dwarfs and the hot subdwarfs. Also, for the luminous but relatively cool variable stars, particularly for the Cepheid variables, IUE observations have allowed the detection and study of main sequence companions, thus providing constraints on the minimum progenitor mass as well as in some cases the present mass for the Cepheid member of the system (see for example the review by Bidelman and Martin, 1987).

In this section, I will emphasize the use of IUE spectra to place constraints on the atmospheric structure of pulsating stars, including Ha emission from shock waves in Mira variables, evidence for color temperatures and velocity fields in stellar variations and carbon stars, the "chromospheric" emission of the Cepheids, and the atmospheric motions of the Cepheids. IUE is particularly well suited to studying atmospheric structure in cool variables because (1) the variability heats portions of the atmosphere (temporarily or permanently) to temperatures near or above 10^4 K, and this typically produces emission features in the IUE spectral region; where also there is more contrast with the photospheric continuum; and (2) there are resonance lines for abundant ions in the IUE range that can be used to detect and study the stellar winds that typically accompany pulsation.

3.1. Nult (Ha) Emission In Mira and Atmospheric Shock Waves

Hydrodynamical models for Mira variables predict that large amplitude shocks should occur -- slightly above or below -- the stellar photosphere, and propagate outward with decreasing velocity amplitude. For fundamental mode pulsation, the initial shock velocity amplitude is expected to be 20-30 km/s or more; this decreases to about 10 km/s (25) at the end of the cycle, when the shock will have moved to ~5 R. In the models, the shocks continue to propagate outward for several cycles, decaying in amplitude (and of course involving steadily decreasing density, emission measure, column density and optical depth).

In Mira variables, Balmer line emission is seen from about maximum light until near minimum light. When the Balmer emission is first seen, however, the relative line intensities are anomalous; this is most easily explained if the emitting region is located under a substantial amount of cool, absorbing dust, and the photons emitted in the different H lines are absorbed by overlying atoms, ions and molecules such as FeI, ClII and TiO (Jay, 1960, 1984).

The Ha emission of Mira can be observed at most phases: the peak emission occurs between phase 0.2 and 0.4 of the visual light curve, or slightly later than the peak in the Halpha lines. Bruessel et al. (1987) fitted Ha emission curves to theoretical models for T eff (P - 30) assuming (1) the Ha flux is a constant fraction of the total shock radiative losses, and (2) the peak in the Ha emission corresponds to the time when the shock reaches an optical depth \( \tau = 2/3 \).

![Figure 1](image1.png)

**Figure 1.** From Bruessel et al., 1987: Shock position, column density above the shock, and shock luminosity for a model with \( M = 1.4 M_\odot, R = 300 R_\odot, T_e = 3000 K \).

The Ha emission in T Cep is consistent with that expected from a rising shock front in a red giant with \( M = 1.4 M_\odot, R = 300 R_\odot, T_e \approx 3000 K \) when the shock is moving from \( -2 \) to \( -5 \) stellar radii. In Figure 2, the total shock luminosity for a model with these parameters is displayed as a function of time. The radiative cooling rate as a function of time, the temperature, density for a gas of normal composition has been used to determine the rate of relaxation towards radiative equilibrium, and hence the net radiative losses (for details, see Bowen, 1980). The shock luminosity is initially dominated by the energetic but short-lived "precursor shock" (see Figure 2). The main shock forms around model phase \( -1.0 \) and propagates outward as it moves outward it traverses regions of progressively lower.
density and its velocity amplitude decreases, so the shock luminosity, \(L_{\text{sh}}\), decreases rapidly with time. This rapid decrease is well matched by the observations, as is shown in Figure 6, where the smooth luminosity curve is the result of correcting the shock luminosity for the effects of overlying absorption. The peak occurs when the net optical depth of the overlying layers is \((2.80 \pm 0.23)\) corresponding to \(r_{\text{shock}} \approx 1.42 R_\odot\). Further comparison with the models indicates that the emission continues to be detectable until the shock has reached 4-5 stellar radii.

![Figure 6](image-url)

**Figure 6.** From Brugel et al. 1987. Top: emergent flux at 2800A assuming that most of \(L_2\) emerges in the MgII h and k lines, for \(k(2800\AA)/R_\odot = 1, 50, 100, 500, 1000, 2000, 4000, 6000,\) and 10,000.

Bottom: fit to observed MgII flux for \(k/R_\odot = 1000.

In the Mira models mass loss results from a complex interaction between the pulsation and the effects of radiation pressure acting on grains (Boden 1986). The pulsation, by raising the density through the outer atmosphere, and by cooling (through adiabatic expansion) parts of the inner atmosphere over part of the cycle, enhances the grain formation rate. One effect of the radiation pressure on the grains is to produce a global cooling of the atmosphere, again due to the adiabatic expansion; this probably further aids grain formation. The outward force due to the radiation pressure also reduces the shock velocity amplitudes -- see Figure 4. The region where the dust is forming and where the material is being accelerated outward as a result is typically from about 2-5 \(R_\odot\). Thus the MgII emission gives us information on the shock through the region where the grains are forming.

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**PULSATING STARS**

35. A New Flyers Luminous in the \(L_2\) Band

The sample of \(L_2\) variables observed with IU includes the peculiar Mira or \(b\) variable \(L_2\) Pup. This star has intervals of 20 years when it exhibits with a period of 140 days and an amplitude of about 6.5 magnitudes, i.e., it behaves like a short period Mira. The historical light curve (from the AAVSO archives) shows, however, that at irregular intervals in the past this amplitude has diminished to <1 magnitude; it is not possible to tell from the AAVSO data whether this period remains the same when the amplitude changes. IU observations of \(L_2\) Pup may have solved the puzzle of these low-amplitude episodes.

For the first two cycles of \(L_2\) Pup observed by Brugel and Wilson with IU, the MgII emission followed the normal Mira pattern, varying by a large factor with maximum emission on the last part of the declining branch of the light curve. For the third cycle, the MgII emission rose only to about 1/3 of its normal maximum, and peaked early; the visual (FES) light curve remained normal. In the fourth cycle, the MgII emission was again low; the visual light curve was flat and had a lower-than-normal maximum.

Since the MgII arises in a shock front at 2-5 stellar radii, and the visible light curve is dominated by emission from deeper in the atmosphere, the fact that the MgII emission showed this effect sooner than the visual light curve suggests that the disturbance originated in the region where dust is most likely to form. An interpretation of the data is that until the third cycle, there was relatively little dust in that region; the shock had the full "nearly ballistic" amplitude expected in the absence of substantial outward driving by radiation pressure on dust. If then dust began to form at \(2-5 R_\odot\), this would decrease the observed MgII emission by decreasing the shock amplitude in this part of the atmosphere. The resultant expansion of the atmosphere due to the radiation pressure acting on the dust would then cause cooling; this could lead to dust formation and reduced shock amplitudes farther in. The reduced visual light curve amplitude seen in the fourth cycle could be either the result of increased visual extinction or decreased BV near \(R_\odot\). Magalhaes et al. (1986) interpreted the long-term variations in the polarization properties of \(L_2\) Pup in terms of the growth of grains on a time-scale of at least a decade, giving independent evidence in favor of this interpretation of the recent episode.

3.3. Semi-Regular Variables and Carbon Stars

The carbon stars studied by Johnson et al. (1986), Eriksson et al. (1986) and the Quercus (1985) include \(TV\) Hor (P ~ 157 days, visual amplitude ~0.4mag) and \(1X\) Psc (irregular variable, visual variation up to 0.41 mag). In both stars, the emission line strengths vary by nearly an order of magnitude. Static models used to fit these spectra require extended "circumstellar", regions with temperatures 5-10,000 K.

While the cause of the irregular variability of stars such as \(1X\) Psc is not clearly known at present, for the \(L_2\) variables pulsation appears the most natural explanation. From the distribution of the periods, the smaller visual amplitudes, and the lack of Balmer emission lines, radial overtones pulsation is suggested. In Figure 7 the velocity, density and temperature structure of the atmosphere
Figure 7. A model by Brown for TW Hya: $L = 1.2 \ M_\odot, T_{\text{eff}} = 3250 \ K, R = 315 \ R_\odot, P = 15 \ \text{yr}, 1 \ \text{hr}$, with dust. As for Figure 4, atmospheric parameters are displayed at two phases. Although dust forms and drives a modest wind, there is an extended region of elevated temperature (a coronal sphere) where the density is $10^{16} \ \text{cm}^{-3}$. 
are shown from a model by Bowen for an overtone pulsator with a period of 152 days, \( M = 2.2 \) \( M_\odot \), \( T_{\text{eff}} = 3250 \) K and \( R = 315 \) \( R_\odot \) corresponding to the parameters for MW Hor adopted by Querci and Querci. Although the physical processes included in the model are the same as for the case shown in Figure 1, and the stellar parameters are not very different, the atmospheric structure is not at all the same. In particular, the presence of an extended "eclipsing" atmosphere in the model appears to be nicely consistent with the observed chromospheric emission.

The MgII h and k line profiles of TX Psc consist of blueshifted emission with self-absorption on the red wing and with absorption features from FeI and FeII superimposed (Trifonov et al. 1990, Figure 1). They noted that the blueshifted emission, together with the absorption that is redshifted relative to the emission, could be explained by a deaccelerating outflow. The line profile of the Mira variable x Cen has also been interpreted in terms of a deaccelerating flow (Cresci et al. 1988). However, the velocity field of the fundamental mode (Figure 4) and overtone (Figure 7) pulsating red giant models accounts equally well for these qualitative features of the line profiles.

For five semi-regular late M giants with periods ranging from 40 to 120 days, Eaton and Johnson (1988) deduced the presence of an extended, turbulent and possibly inhomogeneous chromosphere from IUE observations of MgII, FeII, SiII, and other lines in the long-wavelength band. They cite a characteristic "turbulence" velocity of \(-20\) km/s, which corresponds also to the expected shock amplitude for overtone pulsation in these red giants. As they obtained high-resolution data only at one epoch for each of these stars, it is not possible to determine from the observations whether the line intensities vary with phase in the cycle (as would be expected for shocked emission) or whether they are relatively steady (as would be expected from an extended corona).

A4. Cepheids and the "Hölling-Valtonen Dividing Line"

One early result from IUE, supported by independent observations in X-ray, visual, and IR bands, is the existence of a dividing line or dividing region in the HR diagram between stars that clearly show coronal emission and stars that do not, but are more likely to show indications of extended chromospheres and cool winds (Hölling and Valtonen 1979). The transition occurs in the vicinity of the Cepheid instability strip, which appears rather clearly in spectral type late F among the supergiants in the A main-sequence (Figure 1). Hölling-Valtonen and Dettmann (1984) associated the development of extended chromospheres on the red side of the Cepheid instability strip with the development of surface convection zones; the development of surface convection is believed to govern the location of the red edge of the instability strip (cf. Figure 1 of this paper). Hölling-Valtonen and Dettmann noted that none of the stars to the red of the Cepheid strip showed coronal emission, and none of the stars to the blue showed chromospheric emission.

The observations of coronal emissions were interpreted in terms of a "time-dependent chromosphere" both by Schmidt and Plavec (1983), Hölling-Valtonen, and Hölling-Valtonen and Dettmann (1984). While Schmidt and Plavec related the "ionized atmosphere" to the pulsation period, and hence argued that the emissions produced as a consequence of the pulsational activity, Hölling-Valtonen and Dettmann related the emission to the distance of the star from the edge of the instability strip, and hence to the relative importance of convection below the stellar surface. As we have noted above, pulsation alone can give rise to chromospheric emission in two distinct ways: as time-dependent emission from a rising shock front, and as a more steady emission from an extended "chromosphere." The latter may be distinguished from a true "chromosphere," which is a region that, in analogy with the solar chromosphere, is heated by stochastic (multi-frequency or broadband) waves (acoustic or magneto-hydrodynamic) originating in the convection zone.

The observation of chromospheric emission from Cepheids may be interpreted as due to shocks, color variations, or chromospheres. Static or slowly varying atmospheres are not likely. As a result of pulsation, we expect shock waves to form in the atmospheres of the Cepheids. The simple analytic theory (Hölling-Valtonen and Dettmann 1984; Hill and Willson 1984; Willson and Dettmann 1984) suggests that for the pulsation constants characteristic of Cepheids, \( \Delta v \approx (0.0017 \text{ to } 0.004) \text{ km/s} \). The shock velocity amplitude \( \Delta v \approx 10^3 \text{ km/s} \). Observations of the amplitude of variation of the hydrogen line profiles were made by Hölling-Valtonen and Dettmann (1984). This corresponds to a nearly ballistic motion in the inner atmosphere, where material that is given an outward motion \( \Delta v \approx 10^3 \text{ km/s} \).
by a pulsating shock has just enough time to fall back to its initial position before it encounters the next shock. Thus the material in the inner atmosphere is in motion and essentially in free fall during nearly the entire cycle. The velocity of the material during most of the cycle is also supersonic, so the speed of sound is ~100 km/s. Farther out, both observations and theory indicate that there is an outflow with characteristic velocity ~50-100 km/s, a supersonic wind (Schmidt and Parsons 1982, 1984a,b; Willson 1989 in prep).

The persistence of the chromospheric emission over much of the cycle, particularly for the Cepheids closest to the red edge of the instability strip, formed a part of Balm-Vincent and Quercy's argument in favor of the interpretation of the emission in terms of a chromosphere. However the properties of the pulsation-related calori sphere depends on the effective temperature, the luminosity, and the pulsation characteristics (mode, period, amplitude), properties that also vary across the instability strip. The number of Cepheids that have been observed for chromospheric emission over the cycle is too small to separate these effects. To distinguish between these possibilities will require more data and/or comparison with detailed models.

There are some theoretical points to be made here. While it is probably physically possible to have a true chromosphere (albeit a moving one) in a vigorously pulsating star, this will require that several conditions be satisfied: (1) the frequency of the waves exciting the chromosphere will have to be significantly higher than the frequency of pulsation; (2) the velocity of propagation of these waves will need to be greater than the mean mass motions in the lower atmosphere and (3) the mechanical energy flux will need to be large enough to overcome the cooling effect of the expansion that occurs throughout the cycle between the shocks. This third point also suggests that it is very unlikely that the same chromospheric excitation mechanism will give rise to the same chromospheric emission for a pulsating and a non-pulsating star even given the same $M$, $f$, and $L$.

In conclusion, it is my opinion that there is no compelling evidence for chromospheres in Cepheids, but rather that it is likely that unexplained models including the effects of pulsation will be able to account for all the observations without the need to invoke separate mechanisms. I would divide the HR diagram into two, but three zones: to the blue of the instability strip, we have non-pulsating, coronal stars; in the instability strip, we have an atmosphere that may include a calori sphere energized by mono-periodic waves generated by pulsation; immediately to the red of the instability strip, we have chromospheres energized by phenomena tied directly or indirectly to the surface convection zone.

3.5 Atmospheres in the B and A stars

The velocity and radial position of the "reeversing layer" in a B9o as a function of phase, as deduced from IUE observations by Burger et al. (1982), is reproduced in Figure 9. A comparison of upper and middle panels in this figure with the velocity and radius variations in the HR models of Figures 1 and 4 shows a crude qualitative similarity. The metallic lines may be interpreted as giving information on the motion of material near the photosphere. The CIV lines, in contrast, appear to follow a rising shock front; alternatively, they may be formed higher in the atmosphere where there is an outflow with mean velocity comparable to the shock amplitude. The observed velocity amplitude (including the usual correction factor for the integration of the profile over the limb-darkened disk) at the photosphere is about 100 km/s. From the stellar parameters cited by Burger et al. ($M = 14 M_{\odot}$, $R = 9.2 R_{\odot}$, $P = 2.9488$), I find $Q(R_p) = 0.23$ and $v_\infty(R_p) = 761$ km/s. From Figure 2, then, $Av\approx v_\infty/2 = 380$ km/s. Even taking into account the likely reduction of $Av$ from the ballistic case when pressure gradients are taken into account, I would expect the photospheric shock amplitude to be more than three times the observed $Av$. How can this be explained?

One possibility for reducing the shock amplitude is to reduce the effective gravity, for example by outward radiation pressure. For the early B stars, it is well known that radiation pressure resulting from absorption in UV resonance lines is capable of driving winds without assistance from pulsation or other mechanisms (Carter, Abbott and Klein 1975; Friend and Abbott 1980). To effect the observed shock amplitudes, the radiation pressure...
would need to be strong enough to produce
significant net outward flow quite deep in the
atmosphere of the B Cep star, however; this would
seem to imply a high mass loss rate.

An alternative explanation is that the assumed
values for $u$ and/or $v$ are wrong; that one or both
of these is smaller. To get fully developed shocks
$\approx 100-110$ km/s with the observed periods would
require either reducing $M$ to less than $5M_\odot$ or
Increasing $R$ to about $1.5 R_\odot$. If this is the
photospheric radius, it implies the stellar
pulsation constant is only 0.014$^3$ -- unusually small
for radial pulsation. A third possibility is that the
shock forms only far above the stellar
photosphere. This is expected if the driving is
weak, i.e. the atmospheric damping is small. Then
the photosphere would be located in the region of
standing waves, the undulososphere, where the
amplitude of the motion is smaller. However this
does not seem consistent with the abruptness of the
acceleration of the photospheric layers cited by
Burger et al. Thus I conclude that the small $\Delta v$ are
most likely a result of the importance of radiation
pressure in the B Cep stars, and that these stars probably have substantial winds.

4. CONCLUSIONS

The interpretation of IUE observations of obviously
pulsating stars in terms of static model
atmospheres, models applicable to similar but non-
pulsating stars, or models applicable to stars with
different pulsation properties is always
fundamentally wrong. The atmospheric temperature,
density and velocity structure of a star is very
much altered by the presence of radial (or large-
amplitude non-radial) pulsation, and the structure
depends strongly on the pulsation period and on the
efficiency of mechanisms driving a stellar wind.

For the well-studied radially pulsating stars -- B
Cep variables, Cepheids of all types, and long
period variables -- IUE observations are all at
least qualitatively consistent with the predictions
of models and analytic theory based on the
assumption that pulsation is the dominant factor.

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IUE OBSERVATIONS OF PLANETARY ATMOSPHERES

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ABSTRACT

The UV observation of planetary atmospheres gives access to the upper parts of the atmospheres, below and above the homopause. IUE observations have significantly contributed to our knowledge of the aeronomy and photochemistry of planetary atmospheres. On Venus, SO₃ has been detected; ozone has been observed on Mars; C₂H₂ and NH₃ have been detected in the jovian upper atmosphere; acetylene has been detected also on Saturn and Uranus; aurorae have been detected and mapped on Jupiter and Saturn; the Lyα excess, later interpreted by Voyager as the "electroglow", has been observed on Uranus. The IUE can still be a useful tool for monitoring programs such as ozone on Mars and aurorae on giant planets.

Keywords: planetary atmospheres, UV spectroscopy.

1. INTRODUCTION

The ultra-violet range provides some specific advantages for the study of planetary atmospheres. First, strong emissions from atoms and molecules can be found in this region; second, the UV solar radiation is limited to the upper levels of the atmospheres, due to continuum molecular absorption, absorption and scattering by small particles, and rayleigh scattering. The only exception is the Martian atmosphere which is thin enough for the UV radiation to penetrate down to the surface. In all other cases, the atmospheric layers probed in the UV range are at much higher altitude than the levels probed in the visible, IR and radio range. The IUE satellite is thus an excellent tool to study the upper atmospheres of planets, their aeronomy and their photochemistry.

At wavelengths smaller than 1600 Å, the regions probed are above the homopause; the observed emissions (usually from atoms and diatomic molecules) are produced by resonance recombination, photochemical processes, photoelectron excitation and/or precipitated magnetospheric charged particles. At wavelengths above about 1600 Å, the radiation comes from lower levels, due to the general decrease of the molecular absorption cross sections and the strong Å-dependence of the rayleigh scattering cross-section. More complex molecules can then be observed below the homopause level, down in the stratosphere.

A large number of UV studies have been performed on planetary atmospheres before IUE, using rockets and satellites (references can be found in Moos and Encrenaz, 1987). In the case of Venus, SO₃ was identified from the ground longward of 3000 Å (Barker, 1979). The UV dayglow between 1200 and 1800 Å was observed from a rocket (Rottman and Moos, 1973), showing emission lines of carbon, oxygen and the CO fourth positive system; several emission lines were also detected by Mariner 10 (Broadfoot et al., 1974). In the case of Mars, ozone was detected by Mariner 7 (Barth and Hord, 1971) and subsequently observed by Mariner 9 (Wehrbein et al., 1979); the dayglow spectrum of Mars was observed by Mariner 6, 7 and 9 (Stewart et al., 1972). Jupiter was extensively studied in the UV range before IUE but the results showed large discrepancies (Encrenaz, 1982). However some significant results were already obtained: a broad absorption was observed at 2100 Å and attributed to ammonia (Greenspan and Owen, 1967); a strong Lyα emission was detected on both Jupiter and Saturn (Carlson and Judge, 1974; Judge and Carlson, 1980). In summary, all these preliminary studies demonstrated the potential interest of UV atmospheric studies, but they also indicated the need for systematic measurements by a single well calibrated instrument such as the IUE.

Observing the planets with the IUE is not an easy task (Lane et al., 1978). They are often fast-moving objects and difficult to track, especially the brightest ones. Their UV spectrum, following the solar spectrum, is very steep in the UV, so that different exposures are required to cover the whole
spectral range. Another limitation, for the short-wavelength spectra, comes from the grating scatter of the strong long-wavelength radiation. Finally, a major problem for the interpretation of the data is the acquisition of a solar comparison spectrum; this spectrum should ideally be recorded simultaneously to avoid temporal effects, but this is not possible with IUE. In spite of all these difficulties, IUE spectra of planets have been extensively and successfully recorded, and major results have been obtained on the structure and composition of upper planetary atmospheres, as well as the nature and location of planetary aurorae.

2. VENUS

2.1 The atmospheric composition below the homopause

Sulfur dioxide was first detected by Barker (1979) using ground-based observations; it was later detected in both the middle and lower atmosphere by Pioneer Venus (Stewart et al, 1979) and Venera 11/12 (Gelman et al., 1979). A simultaneous detection of SO₂ was obtained with a high resolution IUE spectrum in the 2000-2200 A range (Conway et al., 1979). The IUE observation had the advantage of offering a high spectral resolution with respect to the spacecraft measurements.

Further observations have shown that SO₂ dominates over COS and H₂S above an altitude of 22km, culminates in the 22-50km region and is converted to H₂SO₄ above this level (von Zahn et al, 1983). Pioneer Venus monitored the SO₂ UV emission over the 1979-1983 period and has shown evidence for a large decrease of the SO₂ mixing ratio at the 40mb level over this time period; a possible explanation might be the episodic injection of sulfur dioxide into the atmosphere by volcanic activity (Esposito, 1984).

2.2 The upper atmosphere

The Venus dayglow spectrum was recorded at high resolution by the IUE in the 1250-1430 A range, showing several atomic oxygen lines and some new components of the CO fourth positive system (Durrance et al., 1980, 1981). The Venus dayglow had been previously observed from rockets and spacecrafts, especially Pioneer Venus, but the IUE observation, with 0.4 A resolution, was the only one showing the resolved CO4+ (14,3) and (14,4) bands, separated from neighbouring oxygen emission lines. From the shape of the CO bands, the excitation mechanism has been identified as solar Lyman alpha scattering (Fig.1). The study of the CO4+ system provides an additional remote sensing technique to determine the CO density distribution in the upper atmosphere.

The Venus nightglow, first observed by Mariner 5, was also detected with the IUE in the low resolution mode (Feldman et al., 1979). This measurement allowed the first identification of the 4-band system of NO; the excitation mechanism has been identified as radiative association of oxygen and nitrogen atoms. This result was subsequently confirmed by the Pioneer Venus Orbiter UVS which was then able to use these emissions to study the transport of atomic nitrogen across the terminator to the night side (Stewart and Barth, 1979).

3. MARS

The study of ozone in the Martian atmosphere is of special interest for understanding the planet's aeronomy. Ozone can be detected by its broad absorption band between 2300 and 2800 A. Previous observations by Mariner 7 (Barth and Hord, 1979) and Mariner 9 (Wehrbein et al., 1979) have shown that there is an anticorrelation between the amount of ozone and the amount of water vapor; this is because the H₂O photodissociation leads to a process which inhibits ozone formation. The H₂O abundance, constrained by the saturation law, strongly depends upon the temperature, and thus shows large seasonal effects. Monitoring the ozone abundance over a seasonal cycle can provide valuable constraints for photochemical and dynamical atmospheric models.

As ozone is expected to be found in the coldest parts of the planet, the most favourable locations are the poles in winter or early spring. A positive detection was achieved with IUE by Conway et al. (1981) who were able to detect the presence of ozone in the vicinity of the poles in the middle of spring (north hemisphere) and who observed its disappearance at the north pole at the end of spring (Fig.2). This result was consistent with previous observations.

Monitoring the ozone abundance of Mars with IUE during the 1988 apparition could be of valuable help for understanding the behaviour and the evolution of the atmosphere a few months prior the
Another important IUE discovery is the acetylene detection, in the 1600-1900 Å range (Owen et al., 1980; Fig. 4). Acetylene comes from the dissociation of methane by the solar UV, and its abundance and vertical distribution provide important constraints for photochemical models. The C$_2$H$_2$ mixing ratio is about $3 \times 10^{-4}$ (Owen et al., 1980; Wagener et al., 1985; Encrenaz et al., 1986). Moreover, an additional continuum absorber is required shortward of 1750 Å. As possible candidates, Wagener et al. (1985) suggest allene and cyclopropane, with mixing ratios of $7 \times 10^{-5}$ and $8 \times 10^{-5}$ respectively.

Above 2300 Å, the UV spectrum of Jupiter is dominated by Rayleigh scattering (Wagener et al., 1985).

4.2 The aurorae

Intense molecular hydrogen emissions (Lyman and Werner bands, between 1550 and 1650 Å) were observed by rocket experiments (Rottman et al., 1973; Giles et al., 1976). The Voyager UVS experiment was then able to map the auroral zones (Broadfoot et al., 1979). The IUE provided complementary observations with a higher spectral resolution (Durrance et al., 1982), and was also able to map the longitudinal distribution of auroral emissions (Fig. 5). As a result, the emissions seem to be restricted to a range of latitudes corresponding to the location of magnetic field lines coming from the Io torus, and central meridian magnetic longitudes between 120 and 250° (Skinner et al., 1984).

IUE observations were also performed to monitor a region of enhanced and variable Lyman alpha emission, the Lyα bulge, in the equatorial region (Clarke et al., 1981; Skinner et al., 1983).

Away from the bulge, the equatorial Lyman alpha emission is nearly constant over magnetic longitude and time. The origin of the emission seems to be resonance scattering of the solar line, but charged particles could also possibly contribute to the excitation mechanism.

![Figure 3: The spectrum of Jupiter compared with models having constant NH$_3$ mixing ratios, ranging from $10^2$ cm$^{-2}$ (1) to $3 \times 10^2$ cm$^{-2}$ (Combes et al., 1980).](image-url)
5. SATURN

5.1 Composition of the atmosphere below the homopause

The most prominent feature of Saturn's UV spectrum is the strong absorption band of acetylene between 1600 and 1900 Å (Fig.6), first identified with IUE by Moose and Clarke (1979); moreover, an additional continuum absorber seems to be required to fit the observed albedo. Winkelstein et al. (1983) found a good fit with a model including C$_2$H$_2$ and C$_2$H$_6$, with mixing ratios of $10^{-7}$ and $6 \times 10^{-8}$ respectively, with, in addition, a layer of water at the top of the atmosphere. The amount of acetylene on Saturn is thus significantly larger than on Jupiter.

Above 2000 Å, the spectrum of Saturn is dominated by Rayleigh scattering (Winkelstein et al. 1983).

Figure 4. The jovian spectrum showing the acetylene bands between 1700 and 1800 Å (Owen et al., 1980)

Figure 5. Spectra of the jovian aurora as a function of magnetic longitude; the orientation of the entrance slit relative to the jovian disk is shown for 3 different spectra. The dashed line indicates the position of the auroral zone (Durrance et al., 1981).

Figure 6. IUE spectra of Saturn, compared with the acetylene absorption coefficient between 1650 and 1900 Å (Moos and Clarke, 1979).

5.2 The aurorae

The Lyman alpha emission of Saturn was, as for Jupiter, observed by rockets, satellites and by Pioneer 11 (Weiser et al., 1977; Judge et al., 1980). Observations of Saturn in the Lyman alpha emission (Clarke et al., 1981) and in the Lyman and Werner bands (Durrance et al., 1982) have been recorded with IUE. The Ly$\alpha$ emission and the H$_2$ bands were found qualitatively similar on Jupiter and Saturn. The emission arises from resonance scattering and by particles excitation. There is indication of auroral activity in the polar enhancements of the Lyman alpha emission and the H$_2$ bands. The Voyager UVS experiment confirmed this result: aurorae were found near 80° latitude, suggesting an Earth-like magnetotail activity (Broadfoot et al., 1981).

6. URANUS AND NEPTUNE

6.1 The acetylene band

Uranus and Neptune, in spite of their apparent similarities, show significant differences: Neptune has a strong internal source, while Uranus has not; the temperature of Neptune is higher in the upper atmosphere, while the Uranus profile above the tropopause is almost isothermal. The UV observation of acetylene is an important tool for studying the methane photodissociation in the upper atmospheres of the two planets.

Observations of Uranus and Neptune with IUE are very difficult at 1700 Å and very long exposures, using double shifts, are required. In the case of Uranus, acetylene has been detected (Caldwell et al., 1984a, b; Encrenaz et al., 1986), with a mixing ratio comparable to the Jupiter abundance (Fig.7). Reduction of Neptune data is in progress;
these observations are clearly at the limit of the IUE capabilities.

Between 2000 and 3000 Å, the spectra of Uranus and Neptune have been analyzed by Caldwell et al (1981, 1984) who have compared the observations with a raman-rayleigh scattering curve.

6.2 The Uranus aurora

After the first observation of a strong Lyman alpha signal on Uranus by IUE (Darius and Fricke 1981), Durrance and Moose (1982) and Clarke (1982), using repeated IUE observations, concluded that Uranus had a significant magnetic field; variations of the strong Lyman alpha signal were monitored with the IUE over almost four years (Clarke et al, 1986).

The existence of the magnetic field was confirmed by Voyager, but the Voyager UVS also discovered that another excitation mechanism - the "electroglow" - was responsible for the Lyα and H2 emissions (Broadfoot et al, 1986). This mechanism, which requires solar energy (as it is not observed on the dark side) is not fully understood presently.

![Figure 7. IUE spectra of Uranus, Jupiter and Saturn between 1650 and 1900 Å (Encrenaz et al, 1986)](image.png)

7. CONCLUSIONS

In spite of the difficulties of planetary observations with IUE, a remarkable number of discoveries have been achieved, and IUE has been a major tool for the study of the upper planetary atmospheres. Atoms and molecules have been detected using long, double-shift exposures; monitoring of auroral phenomena has been achieved over several years. In many cases, the IUE observations have provided very precious help in complement to spacecraft observations, such as Mariner 9 on Mars, Pioneer on Venus, Voyager on the giant planets.

Over the past ten years, the IUE has been used to the best of his capabilities for planetary studies. In the future, IUE might still be very useful for monitoring long-term variable phenomena, in connection with future space exploration. A possible observation of ozone on Mars has been mentioned above; monitoring the jovian aurorae would be useful in the frame of the International Jupiter Watch, in preparation of the Galileo mission; there is still much to learn about the "electroglow" mechanism on Uranus; detecting acetylene on Neptune would be of special interest in connection with the future 1989 Voyager observations.

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COMETS

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ABSTRACT

Over the 1-2 years since the last major reviews of this topic, IUE has been used to study several additional comets including the first dynamically new comet to approach closer than 3 AU. Thus for the first time, we can begin to draw some conclusions about the differences between old and new comets. This review emphasizes the results relevant to the nature of cometary nuclei.

Keywords: comets, spectroscopy, chemical composition, cometary nuclei.

1. INTRODUCTION

One of the primary goals of cometary astronomy is to determine the physical structure and chemical composition of the usually undetectable cometary nucleus because it is commonly accepted that knowledge of nuclei will place important constraints on the conditions in the proto-solar nebula when the planets were formed. With only a handful of exceptions, our knowledge of cometary nuclei is based entirely on observations of the gas and dust in the coma, a task for which IUE is extremely well suited because its spectrometers cover the principal resonance lines of several molecular species as well as of most of the cosmically abundant atomic species.

The step from measuring these species in the coma to estimating the composition and structure of the nucleus is, not surprisingly, a rather difficult one which requires that we fully understand a wide variety of relevant physical processes which occur in the coma. Despite the series of spacecraft encounters with comets Giacobini-Zinner and Halley, our understanding of these processes is well-developed in only a few areas. Observations with IUE have also played a key role in understanding these processes.

Recent reviews of the IUE observations of comets by Festou and Peltman (Refs. 1, 2) have summarized the results through the preliminary analyses of the observations of Comet Halley. For this review on the tenth anniversary of IUE, one might dwell primarily on a complete review of what has been learned in those ten years. Because the two previously cited reviews covered the earlier advances so well, we can emphasize the more recent results although the context will be discussed. One might expect that the additional year or two of observations and analysis would not have led to significant advances over the previous 8 to 9 years but this is clearly not the case both because some particularly interesting comets were available in the last two years and because our understanding of the observations of Halley is continually improving.

Observations of comets are notoriously difficult under any circumstances and with IUE some of these complications are exaggerated even more. These include the need to observe at the smallest elongations possible, frequently involving discharging the spacecraft batteries in recent years, the fact that often a comet must be observed very soon after it is discovered and before its orbit is well known, the fact that comets sometimes move much faster than any other target observed with IUE, and potentially the most difficult, the fact that all interested scientists must get their observations at the same time. These difficulties have all been overcome with remarkable success due to the outstanding performance of the telescope operators and resident astronomers and to a remarkable degree of cooperation among the interested scientists. This has allowed, e.g., blind offsets on a very rapidly moving comet, many-hour exposures on a comet moving at more than an arcsecond per second of time at non-uniform rates, several 12-hour exposures combining Vilspa and Goddard shifts, and the ability to observe comets within days of their discovery.

2. SCOPE OF THE OBSERVATIONS

The previous reviews (Refs. 1, 2) listed 26 comets observed with IUE through mid-1986 of which only one, P/Encke had been observed at more than one apparition. The total number of comets observed has now increased to 32, of which P/Encke has now been observed at a third apparition and P/Borrelly at a second apparition. These additional observations are important for two reasons. The repeated observations of the same comet at successive apparitions allow us to determine which aspects of the comet's behavior are regular and repeatable and which might be transient phenomena, historically one of the more challenging aspects of cometary astronomy. Over a sufficiently long interval one
can also look for secular trends in the behavior of periodic comets but ten years is far too short a baseline for that. The observation of additional, previously unobserved comets is important also in order to understand the distribution of cometary properties over the ensemble of all comets.

Table 1A lists the observations that have been made as a function of the dynamical history of the comet. The new comets are those that are entering the inner solar system for the first time from the Oort cloud, presumably due to a recent perturbation by a passing star. They have essentially zero binding energy as expressed by the reciprocal semi-major axis prior to planetary perturbations, \((1/a)_0\). These cometary nuclei should exhibit the original surface produced when the comet formed, modified only by 4.5 billion years of exposure to cosmic rays. Successive passages through the inner solar system, with the accompanying planetary perturbations, lead in a random walk either to more tightly bound orbits or to ejection from the solar system. They also lead to release of volatiles from successively deeper layers in the nucleus. The short-period comets, which are most tightly bound to the sun and somewhat arbitrarily divided from the long-period comets, are, at least statistically, releasing gases from what were originally the deepest layers in the nucleus, perhaps through a relatively inert mantle developed on previous perihelion passages. It is therefore important to understand whether or not there are significant differences in composition or other behavior with dynamical age. The comets listed as well studied are those that were observed at four or more different points in their orbits covering a significant range of heliocentric distance and/or time. These comets are listed individually in Table 1B and represent the only comets for which we have enough data to make useful statements about the variation with time and/or heliocentric distance. Most of the other comets were observed only during a single shift, either to investigate particular physical problems or to improve our knowledge of the distribution of compositions.

The table gives the type of comet, the identification, the perihelion distance, the time interval of the observations, and the range of heliocentric distances from both pre- and post-perihelion. For many reasons P/Halley was the best studied although the results from Comet Wilson are at least as interesting. These two comets were comparably bright and comparably deep exposures were obtained on both, exposures up to 12 hours. Because most of the comets have low surface brightness, the bulk of the observations have been made at low dispersion and, with only one exception, all the high-dispersion exposures have been on the comets listed in Table 1B as well studied. Similarly with very few exceptions, it is only the comets in Table 1B for which exposures were made at any position other than centered on the photocenter.

The result of this pattern of observations is that there is a handful of comets on which we have made observations diagnostic of physical processes and which can tell us directly about the chemical abundances. For another two dozen comets we have a "snapshot" or two which can be used, together with the models derived from the well observed comets, to estimate the chemical composition at a
particular moment and thereby approach the question of the distribution of abundances among comets. These data can also be used as an ensemble to study the variation of abundances with heliocentric distance. Because of space limitations, this review will emphasize the empirical nature of comets while omitting many of the recent advances in understanding physical processes such as excitation mechanism, dissociation/ionization processes, and so on. For that reason, this review is selective rather than comprehensive.

3. IDENTIFICATION OF NEW SPECIES

Qualitatively low dispersion spectra of most comets look very similar (Ref. 21) and Figure 1 shows a typical recent composite spectrum from both LWP and SWP cameras. Many of the identified species were identified prior to the launch of IUE in rocket spectra of Comet West 1976 VI (Refs. 3,4) although the IUE data have allowed the definitive identification of several species of major importance.

As discussed in earlier reviews, the Mulliken bands of $\text{C}_2$ at $\lambda 2320$ were first positively identified in IUE spectra of Comet Bradfield 1979X (Ref. 5) as was the $S-3P$ transition of [OI] at $\lambda 8972$ (Ref. 6). Although these features had not been previously observed, their existence could have been predicted from the existence of spectral features of the same species at optical wavelength. Similarly, bands of OH have been identified (Ref. 7).

The next new identification came in 1983 with the remarkably close ($0.03$ AU) passage of comet IRAS-Araki-Alcock 1993 VII. At the time of closest approach, $S_2$ was the second most prominent emitter, second only to OH, in the LWR spectrum as shown in Figure 2 (Ref. 8). It is extremely unlikely that Figure 2. Spectra of C/IRAS-Araki-Alcock (a) centered on the nucleus and (b) offset by one slit length from the nucleus. The $S_2$ is visible only within a few hundred km of the nucleus.

Figure 1. Composite spectrum of P/Halley on 1986 March 9. The OH bands were saturated and the continuum between 2800 - 3000 Å were overexposed in the non-linear region of the JTF.
this species could have been predicted since it is extremely unstable and has still never been convincingly detected in any other celestial source. Furthermore, it was only the existence of an outburst by the comet at the time of closest approach coupled with the in situ spatial scale (25 km/arcsec) which made the detection possible although Wallis and Krishna-Swamy (Ref. 9) have suggested that $S_2$ is weakly present in the spectra of several other comets. The existence of this species, presumably in all comets despite the lack of other convincing detections, has been used to argue that the cometary ices were never very warm after their formation as the mantles of interstellar grains (Ref. 10).

Experimental work by different groups (Refs. 11, 12) has not only raised somewhat the estimate of the highest temperature to which the ices could have been heated but also shown, as was expected, that other sulfur-bearing species should be present, particularly $SO$ and $SO_2$, if the proposed scenario for formation of $S_2$ is correct. Wallis and Krishna-Swamy (Ref. 9) have argued that $SO$ is present, e.g., in the IUE spectra of comet IRAS-Araki-Alcock. This is certainly the best comet in which to search for $SO$ since $SO$ should appear close to the nucleus and should therefore be most visible in the comet that was closest to Earth. In an attempt to further test this important identification, Kim (private communication) has calculated theoretical fluorescence spectra of $SO$ in order to predict more accurately the shape, position, and relative intensities of the $SO$ bands. Figure 3 compares that calculated spectrum with an observed spectrum of comet IRAS-Araki-Alcock from which the reflected solar continuum has been removed by fitting at longer wavelengths. We believe that the fitted spectrum of $SO$ corresponds to roughly a 1–2 upper limit since the profiles do not match the peaks in the observed spectrum. The column density of $SO$ which would produce a spectrum of this intensity corresponds to a production rate roughly an order of magnitude greater than that of $S_2$ in the same comet. This is certainly a plausible result in terms of the ratio of $S_2$ to $SO$ seen in the laboratory experiments but it runs into difficulty with the total amount of $S$ since $S_2$ and CS can account for only about a factor of 3 higher abundance of $S$ expected in comets and the observed emission of atomic $S$ in comets (but see next paragraph).

Although these results are uncertain by a factor two, an order of magnitude higher abundance would be difficult, although probably not impossible, to reconcile with these data. It is clear that the search for other sulfur-bearing compounds, specifically $SO$, $SO_2$, and $H_2S$, is an extremely important one since the presence or absence of these compounds at abundances comparable to that of $S_2$ is critical in assessing whether or not our hypothesis for the source of $S_2$ is correct. Although the work of Wallis and Krishna-Swamy (Ref. 9) is an important stimulant, a definitive identification and determination of the abundances of these species will require an order of magnitude improvement in signal-to-noise ratio compared to data reduced and presented to date.

The most recent identification is of the $S_1$ triplet at $\lambda 1425$ and $1474$ by Roettger et al. (Ref. 13) in Comet Wilson 1986II. Although the $S_1$ triplet at $\lambda 1814$ has been known for some time, these other multiplets had not been previously reported and were discovered here primarily because the emission at $\lambda 1474$ is pumped by a solar emission line and is thus strong only at heliocentric velocities near 0, a situation which normally occurs when a comet's solar elongation is too small for observation with IUE. Surprisingly, the ratio of these new multiplets to that at $\lambda 1814$ is inconsistent by a factor of 5 with a straightforward fluorescent pumping mechanism using solar emission lines. Although anomalies in the relative strengths of the triplet components at $\lambda 1814$ suggest that optical depth may be significant in that multiplet (Feldman, private communication), these new results may require a comprehensive investigation of the fluorescent efficiencies of all the $S_1$ multiplets. This could increase the total amount of $S$ by a factor of 5 and thus remove one of the difficulties cited above with respect to a high abundance of $S_0$.

A potentially important identification would be of $OD$ since the ratio $OD/OH$ is characteristic of the formation process of the icy grains. The most sensitive search thus far published is only an upper limit $OH/OH < 4 \times 10^{-4}$ (Ref. 14), consistent with the upper bound from in situ measurements by Glotko (Ref. 15). A more sensitive search will be an important future task.

4. RELATIVE ABUNDANCES

Observations of species easily measured in the optical have shown no systematic difference in the composition of new and old comets (Refs. 16–18) even though very different photometric behavior is a well-established characteristic (see above). The same optical observations have shown that, with remarkably few exceptions, the total scatter in relative abundances from comet to comet is little more than a factor of 2, i.e., only slightly larger than the uncertainties inherent in most of the data except for some comets noted below. The only compositional parameter known to vary dramatically from one comet to another is the gas-to-dust ratio but this is not correlated with the dynamical age of the comet using either optical data (Ref. 19) or data from IUE (Ref. 20). One might expect to find compositional differences in the ultraviolet where quite different species are observable. However, as originally pointed out by Weaver et al. (Ref. 21) and noted further in previous reviews (Ref. 1, 2), the relative abundances determined...
With IUE in most comet comae seemed remarkably uniform but no dynamically new comet had ever been observed in detail or with sufficient sensitivity with IUE until Comet Wilson in 1986-87. The two other dynamically new comets (Bowell 1982, Comet IRAS 1983) observed with IUE had perihelion distances beyond 3 AU and were therefore observed only close to perihelion when very long exposures were barely sufficient to show the very strong 0-0 band of OH.

The interesting abundances, of course, are those of the parent molecules in the nucleus since it is these abundances which will tell us about the formation of comets. If the abundances are uniform from comet to comet and with depth in the cometary nucleus, one can argue for homogeneous accretion in a uniform (or at least well mixed) region of the solar nebula. Variations from comet to comet or between old and new comets can tell us respectively about spatial variations in the nebula and about temporal variations during the accretion stage. These abundances must be inferred from measurements of column densities in the coma. This naturally requires a good knowledge of the physical processes involved, something we are skipping over in this review. For some easily observed species, such as OH and CS, a single parent molecule (likely H2O and C2H2 respectively) is likely to produce all molecules of the observed species and the spatial distribution has been measured either with IUE or with other instrumentation so that one can make reasonable inferences about the ejection of the parent molecules based on a measurement of the column density of the fragment. For these species, therefore, one can ask how the production rate varies with heliocentric distance or from one comet to another. For other species, such as CO2+, it is much more difficult to interpret a column density of the observed species in terms of the production of its parent (presumably CO). As a result, one can realistically compare one comet with another only by choosing comets observed with similar geometries, i.e., at similar geocentric and heliocentric distances. Fortunately, there now exists a sufficient ensemble of cometary observations that one can often find such a comparison for any given observable and thereby boot-strap one another. When looking at atomic abundances the same problems are compounded because most atomic species have multiple parents and, except for H, the spatial distributions are not well studied. For this reason it is best to compare atomic abundances in the same way one does CO2+ i.e. by comparing comets observed at comparable geocentric and heliocentric distances. The easily observed line is not normally used to determine the column density of H because it is optically thick and a single measurement on the nucleus is not easily interpretable. Models exist (Refs. 22, 23) for interpreting these data if the spatial distribution is measured but such data are better obtained from rockets and other spacecraft with imaging or scanning systems (e.g., Pioneer Venus Orbiter) than with IUE.

### 4.1 New Comets vs. Old Comets

With the advent of Comet Wilson 1986, Roettger et al. (Ref. 13) have finally succeeded in using ultraviolet data to address the question of relative abundances in a new comet in comparison with those in old comets. Fortunately, P/Halley 1986 II was observed before perihelion at geocentric and heliocentric distances comparable to those of C/Wilson near perihelion. Furthermore, the production rates of OH were nearly the same in the two comets at these times so that the effects of density-dependent chemical processes in the coma should be similar for both comets and any differences in column densities must be attributable to differences in nuclear composition. Table 2 excerpts some of the results from Ref. 13.

### Table 2

<table>
<thead>
<tr>
<th>Cometary Observations</th>
<th>Abundances in a New and an Old Comet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pre-</td>
</tr>
<tr>
<td>n(H2)</td>
<td>1.24</td>
</tr>
<tr>
<td>n(C02)</td>
<td>0.85</td>
</tr>
<tr>
<td>n(QS)</td>
<td>1.34</td>
</tr>
<tr>
<td>n(CS)</td>
<td>2.0</td>
</tr>
<tr>
<td>n(QO)</td>
<td>7.7</td>
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<tr>
<td>n(0H)</td>
<td>&lt;150</td>
</tr>
<tr>
<td>n(CT)</td>
<td>9.5</td>
</tr>
<tr>
<td>n(O1)</td>
<td>48.8</td>
</tr>
<tr>
<td>n(S1)</td>
<td>7.5</td>
</tr>
<tr>
<td>n(QH20)</td>
<td>&lt;85</td>
</tr>
<tr>
<td>n(QCS2)</td>
<td>246</td>
</tr>
<tr>
<td>n(QCS2)</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Examination of those numbers shows that most species have virtually identical abundances in both comets providing a perhaps surprising confirmation of the similar conclusion regarding optically observed species. The only exceptions are that C and S are both underabundant by roughly a factor 2 in the new C/Wilson relative to the old P/Halley and even these differences are barely pushing the limits of the scatter among optically determined abundances. All of the measurable parents of these species, however, have abundances similar to those in Halley thus emphasizing the difficulty of interpreting the atomic abundances. Although no explanation has been suggested for the difference in column density of S other than an unknown parent (CS differs much less between the two comets), it is plausible to suggest with Roettger et al. (Ref. 13) that the difference in the column density of C is due to a difference in the abundance of CO which is known to be the second most abundant volatile in P/Halley (Refs. 24, 25). Although CO was undetectable in C/Wilson at any time and in P/Halley at the time the geometrical circumstances matched those of C/Wilson, it was readily detectable with IUE on P/Halley was closer to perihelion (see Figure 1) and the relative abundance at that time is consistent with all the upper limits for both P/Halley and C/Wilson in Table 2. Optical data on the forbidden lines of [O I] have been used to infer significant variations in the relative abundance of CO or CO2 from comet to comet (Ref. 26) but the required confirmation with direct observation of CO in numerous comets in the ultraviolet must await.
either a breakthrough in extracting weak signals from IUE spectra or a spacecraft with the next generation of instrumentation.

4.2 Two Anomalous Comets

There are two comets observed with IUE, out of a total of 32 comets, which show significant compositional anomalies - P/Encke and P/Giacobini-Zinner. These two comets also show significant compositional anomalies in the optically observed species and they are the only two comets for which major compositional anomalies have been quantitatively well documented at relatively small heliocentric distances (see Ref. 27 for anomalies at larger distances). It should be remembered that most species observed either with IUE or in the optical are trace species compared to OH, H, C, and O. All other species readily observed imply abundances of their parents in the nucleus less than 1% that of H.2. Only CO is known to have an abundance which is significant and because its g-factor (fluorescence efficiency) is so low it is observable only under optimum circumstances in bright comets.

Comet P/Giacobini-Zinner, the first comet visited by a spacecraft, has been known for decades to exhibit anomalous relative abundances of the optically observable trace species. During the last apparition, abundances were first determined relative to OH in both the optical and the ultraviolet providing the normalization necessary to interpret the anomaly. In the optical ON has a normal abundance while NH, C2, and CO2 are depleted by roughly an order of magnitude (Refs. 28, 29). A spectrum taken with IUE is shown in Figure 4 (Ref. 41). A comparison with Figure 1 suggests that the relative abundance of CS is "normal" and a quantitative analysis confirms that it is. The abundance of NH, however, is strongly depleted relative to OH even after taking into account the poor signal-to-noise ratio at the wavelength of the NH band and variations in the g-factor for OH. The NH band is undetectable in P/Giacobini-Zinner (Fig. 4) whereas it is stronger than that of CS in P/Halley (Fig. 1). If it were not for this depletion of NH, one would be tempted to attribute the anomalies to depletion of carbon polymers in the nucleus but not of other carbon compounds. With the strong depletion of NH, however, the nature of the depletion in the nucleus is unclear and, as yet, uninterpreted. Whether this implies formation of this cometary nucleus in a different part of space than most cometary nuclei or is an evolutionary effect is not yet known.

The anomalies in P/Encke are even more unusual than those in P/Giacobini-Zinner since the relative abundances are normal preperihelion and anomalous post perihelion. In this case, furthermore, all trace species are depleted relative to OH. Figure 5 shows IUE spectra of P/Encke before and after perihelion at similar heliocentric distances and the difference in the relative strength of CS and OH is dramatic. Although some of this difference is due to differing g-factors and to differing geometries, the production of the parent of CS is down by a factor of 4 postperihelion (Ref. 30) as are most optically observed trace species. Sekanina (Ref. 31) has modelled the
nucleus of P/Encke and concluded that the emission at the two times corresponding to Figure 4 is from two quite different active areas on the nucleus, one near the north pole of the nucleus preperihe­lion and one near the south pole postperihe­lion. Why these two areas should exhibit such different compositions, however, is not understood. We note that P/Encke might well be the most highly evolved comet known since it has undergone more observed passages close to the sun than any other. This evolution is known to have affected the two hemi­pheres differently so that anomalous abundances may be an effect of mantle formation rather than a primordial heterogeneity in the nucleus. This question has thus far not been addressed.

Although these two comets are dramatically different from others, I would like to stress that they are rather rare exceptions to the pattern. Most comets exhibit very similar compositions as measured with IUE. The challenge is to find other species which can be measured in a large number of comets with CO being the most tantalizing possi­bility both because of its high abundance in P/Halley and because of the indirect evidence that it may vary significantly from comet to comet.

5. VARIABILITY OF COMETS

Two types of variability are important in understanding the behavior of comets—the overall variation with heliocentric distance and shorter-term variations. Both types of variation can tell us about the cometary nucleus. The overall vari­ation can tell us about the volatility of the ice which controls the vaporization, e.g., whether the dominant ice is water or a more volatile species such as CO, and about the existence and blow-off of refractory mantles. The shorter term variation can tell us about cometary rotation, the homoge­neity of the surface, and the degree of coverage by a mantle. Observations with IUE are particu­larly valuable because the OH bands monitor the production of water vapor, the species that is known to be the most abundant volatile in P/Halley and thought to be the most abundant in most comets.

5.1 Variation with Heliocentric Distance

Most comets observed with IUE have shown a fairly steep variation in the production of OH as a function of heliocentric distance inside 2 AU. Figures 6, 7, and 8 show three examples. C/Bradfield 1979 X was the first comet whose variation with heliocentric distance was studied with IUE (Ref. 32). In the range 0.5 < \( r_H < 1.5 \) AU, the variation in production of water is reasonably smooth, varying as \( r^{-3.7} \), as the comet receded (the comet was not observable before perihelion). P/Giacobini-Zinner was observed over a rather small range of heliocentric distance although the range of time was three months (Ref. 33). It too varied smoothly and steeply but with the peak outgassing occurring a full month before perihelion. P/Halley was seen to vary steeply for heliocentric distances beyond 1.5 AU but relatively slowly at smaller distances (Ref. 24). P/Halley could not be observed with IUE near perihelion but for distances beyond 1 AU the comet was outgassing much more rapidly after perihelion than before.

The production of solid grains can be charac­terized by the quantity \( A_{Fp} \) which is directly proportional to the production of solids as long as outflow velocity of the solids, scattering

Figure 6. Production of water by C/Bradfield 1979X. A straight line through all but the last point corresponds to variation as \( r^{-3.7} \).

Figure 7. Production of water by P/Giacobini-Zinner 1985 XIII. Note the sharply peaked variation centered at a point roughly one month before perihelion followed by nearly constant production 1 to 2 months after perihelion.

Figure 8. Production of water by P/Halley 1986 III. Note that the production is systematically higher after perihelion than before.
properties, etc. remain constant. Although there appear to be significant variations in the ratio of gases to solids with heliocentric distance (Ref. 20), the production of dust is like that of water in varying steeply with heliocentric distance at least for some distances inside 2 AU although, unlike that of water, the production of dust in P/Halley continued to increase inside 1 AU as shown in Figure 9 (Ref. 20).

Figure 9. Production of solid grains by P/Halley as measured by the parameter \( \Delta F_p \). This is proportional to the production rate if scattering properties and outflow velocity remain constant.

These results can probably be generalized to the ensemble of comets, other than new comets, on the basis of visual magnitudes. They suggest that nearly all short- and long-period comets vary steeply in brightness, and therefore presumably in vaporization of water, inside 2 AU. They also suggest that asymmetries about perihelion are common and that the comets are comparably likely to be brighter before perihelion or after. The results from LUE imply that the outgassing of water behaves in this same manner and probably controls vaporization in all these comets. All of the above behaviors can, at least qualitatively, be understood as a combination of vaporization controlled by water, seasonal variation due to obliquity of the polar axis, shielding/heating by dust in the coma, and mantle coverage of a significant fraction of the surface.

The behavior of new C/Wilson was totally different. Figures 10 and 11 show the variation in the production of water and of solid grains in C/Wilson (Ref. 13). The release of water varied steeply as the comet first approached 2 AU but no faster than \( r^{-1} \) inside that distance, and it actually decreased smoothly as the comet approached perihelion (1.2 AU). The vaporization of water was systematically lower after perihelion. Beyond 3 AU, C/Wilson was an order of magnitude more active than P/Halley. The behavior of the dust was even more extreme since the production decreased almost monotonically from outside 3 AU through perihelion. It is interesting to note that new comets Bowell (Ref. 34) and Cernis were also both observed near perihelion near 3 AU and were also found to be emitting significant OH. It has been widely observed that dynamically new comets have unusually shallow visible light curves on first approach to the inner solar system (Ref. 35) having brightened sharply at large distances. This has been interpreted as being due to the vaporization of the outermost layer of the nucleus that has been made more volatile by irradiation with cosmic rays during 4.5 billion years in the Oort cloud (Ref. 36-38). The clear extension of that interpretation is that many of the grains released at large distances are large, icy grains which begin to evaporate when the comet reaches 4 to 5 AU. These grains then provide a significant fraction of the OH seen in new comets at that distance and their vaporization also explains the apparent decrease in production of grains. Once the comet reaches about 3 AU, the vaporization of the nucleus again becomes significant both adding to the OH and increasing the apparent production of grains. The new comets then behave like more typical comets when receding from the Sun. This general scenario explains most of the data. Detailed models of C/Wilson have not yet been constructed to test the picture quantitatively. Explaining the difference between the behavior of new comets and old comets is likely to be the key in understanding the irradiation of comets in the Oort cloud.

5.2 Short-Term Variability

One of the dramatic results from the observing program on P/Halley was the short-term variability with very large amplitude. Since P/Halley was
studied no much more intensively than any other comet, one might ask whether this variability was seen only because we looked harder or whether it is a common phenomenon, whether it is limited to certain heliocentric distances, and whether it is limited to old comets or occurs in new comets also. With the limited statistics of only one new comet observed with IUE, it is impossible to answer this question based solely on the data from IUE.

Figure 12. Light curve of P/Halley in December 1985 as measured with the FES. Note the onset of large-amplitude variability in mid-December.

Figure 12 shows the onset of the variability as measured with the FES in P/Halley between 1.25 and 1.1 AU. One of the free extras with IUE is a broad-band visible photometer which is free of atmospheric effects and therefore able to provide long-term monitoring of brightness. Since the tracking of the spacecraft is checked frequently when observing comets, we get frequent measurements of the brightness which yield a light curve such as that in Figure 12. It is clear that there was a dramatic change in P/Halley's behavior in mid-December since prior to that time FES counts during a shift always remained relatively stable during a shift, like the observations on the left half of the figure, whereas from mid-December until June of 1986 there was a significant variability, like that in the right half of Figure 12, in the FES counts during each shift. The spectrometers on IUE do not provide such good temporal resolution but the variability of Halley was still obvious in the spectra. Figure 13 shows the production of H$_2$O and CS by Halley when it first satisfied the pointing constraints of IUE after perihelion (Ref. 39). Variations by a factor 3 from day to day are clear. Similar variability has been observed at 1 AU in some other old comets, such as IRAS-Araki-Alcock 1983 VI (Ref. 10), but other old comets have been observed to be very steady at 1 AU, such as P/Giacobini-Zinner (Ref. 33). Prior to IRAS-Araki-Alcock, cometary observers had not realized the value of the FES in monitoring the comet but there are suggestions of short term variability in the gaseous production rates of C/Austin 1982 VI shown in Figure 14 (Ref. 40). The deviations from a smooth variability with heliocentric distance may be indicative of short-term variability although they need not be due to this. I infer that short term variability is common but not universal among old comets. The plausible interpretation in the case of P/Halley is that the variability set in when one of the active areas, photographed subsequently with the Vega and Giotto spacecraft, broke through a mantle of non-volatile material. Whether this process is characteristic of old comets remains to be seen.

Figure 13. Variability of water production by P/Halley in March 1986. Although this does not have the temporal resolution of the FES data, it is clear that the vaporization varied by a factor of a few from day to day.

Figure 14. Variation of water production by C/Austin 1982 VI as a function of heliocentric distance. The significant variations around a smooth curve may be indicative of short-term variability as in P/Halley.

C/Wilson, on the other hand, exhibited absolutely no short-term variability. The variation of production rates varied smoothly with heliocentric distance (see Figures 10 and 11 above) and the FES varied negligibly over long periods as shown in Figure 15. Over 24 hours on April 3-4 the FES varied by less than 5%. This behavior persisted over the entire apparition. Unfortunately we do not know if this behavior is due to the fact that the comet is a new one or due to the fact that it did not approach quite close enough to the Sun to
 trigger the short-period variations. Certainly comet Kohoutek 1973 XII, another dynamically new comet observed with many techniques, showed many signs of short-term variability after it was inside 1 AU but it was not well enough observed before passing inside 1 AU to know whether variability was present at distances comparable to those of C/Wilson.

It is possible that a new comet must pass close to the Sun (say 0.5 AU) in order to form a significant mantle whereas several passes at larger distances are enough of a mantle that long-period and short-period comets can exhibit outbursts at larger distances from the Sun. In the absence of data on more dynamically new comets, however, this is pure speculation.

6. COMETARY MASSES

One of the most fundamental properties of any celestial body is its mass — a property that has never been measured, except in model-dependent ways, for any comet. In the case of a comet, the more interesting property is the mean density which could be determined if mass and radius were known since the density will constrain the accretion process by which the comets formed.

Although upper limits to cometary masses have been determined from the absence of gravitational interactions, the closest we have come to the measurement of a mass is by modelling the nongravitational acceleration which is produced by the rocket-like ejection of gas preferentially from the hottest part of the surface, i.e. at the part of the surface in local "afternoon" (Ref. 41).

Data from IUE have now been used to measure the velocity of the OH in P/Encke with unprecedented accuracy, to better than 1 km/sec, by using the Greenstein effect, the variation in relative line strengths due to differing heliocentric radial velocities within the cometary coma. Unlike a direct measurement of the Doppler shift, this method requires only that the wavelength of an emission line be determined accurately enough to uniquely identify the line but it does require a photometric calibration. Although the method is not generally applicable, it is applicable to any source shining by fluorescence pumped by a source with strong absorption or emission lines at the wavelengths of interest. The effect is seen in

Figure 15. FES light curve of C/Wilson 19861 for 24 hours in April 1987. The visible light is constant to within 5% over this period.

Figure 16. Observed and theoretical spectra of OH in P/Encke before and after perihelion. The dotted curve is computed for the radial velocity of P/Encke's nucleus (and offset in wavelength for clarity) while the dashed curve is computed for the "best-fitting" velocity. In the pre-perihelion spectrum the offset is 1.6 km/sec and the agreement of the relative intensities of the lines is remarkably improved.

Figure 16 shows two spectra of P/Encke, one before perihelion and one after, both near r = 0.8 AU. The dashed lines represent theoretical spectra (offset in wavelength) at the nominal velocity of P/Encke's nucleus and offset to the "best fitting" velocity (Ref. 42). The pre-perihelion spectrum is fit far better with an offset velocity than with the nominal velocity. This offset velocity can be combined with the production of water determined from the brightness of the OH emission to yield the nongravitational force. A reanalysis of the nongravitational acceleration (assuming forces that vary with heliocentric distance in way consistent with the latest data) will then lead directly to the mass of the nucleus. We have presented a preliminary analysis of these results but reanalysis of the orbital data has not yet been completed. Furthermore, the radius of P/Encke is not well determined so it is not yet clear whether the nongravitational forces in other comets will be measurable since the ejection must be extremely anisotropic to produce a significant Greenstein effect. If the same nongravitational force is produced with a smaller anisotropy but a correspondingly larger rate of outgassing, it will
not be detectable with our present signal-to-noise ratio since the intensity ratios in the present spectra allow no better than ±0.5 km/sec.

This recent result, which is based on archival data from 1980, suggests that there may be many other new ways to use the IUE data to answer questions previously thought to be outside the capability of IUE. The use of the archival data will be limited only by the creativity of the users.

7. ACKNOWLEDGEMENTS

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Some Recent Results from the Study of Cool Stars

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ABSTRACT

Selected topics in the area of cool stars are briefly reviewed for they well illustrate unique and scientifically rewarding use of IUE, and the pressing need for both multifrequency measurements and continuous measurements of cool stars in order to explore new aspects of stellar evolution and atmospheric structure. The four topics considered are: circumstellar disks around low mass stars; extended atmospheric structures in cool dwarf stars; pulsation as a common phenomenon in luminous cool stars; magnetic activity cycles in dwarf stars.

Keywords: Accretion Disks, Cool Stars, Magnetic Activity, Mass Loss, Pulsation

1. INTRODUCTION

The IUE satellite has contributed substantially to our understanding of the physics of cool stars. Articles in the review volume: Exploring the Universe with the IUE Satellite (Ref. 1) demonstrate clearly how IUE has provided the first comprehensive picture of the outer atmospheres of cool stars, has delineated the presence and character of stellar winds across the cool half of the HR diagram, and discovered the evolution of outer atmospheres of cool stars. Many review papers (see Refs. 2-6) have organized and presented results from the first decade of the IUE.

In this Review, I would like to highlight areas of research in cool stars that demonstrate the recent contributions of IUE to cool star physics. A decade’s observations with IUE have resulted in a tool that is fully integrated into an astronomer’s “standard equipment.” It is also apparent that a broad energy range of measurement is necessary to address important questions in stellar physics. Additionally, the longevity of IUE has opened a new dimension in stellar observations - that of the continuous measurement, which has revealed unexpected phenomena and allows exploration of new questions relating to stellar magnetic activity.

Figure 1. Schematic drawing of the circumstellar disk and boundary layer surrounding a cool star. Radiation from the boundary layer for a T Tauri-like system is believed to produce the ultraviolet continuum and may contribute to the high temperature emission lines. (Diagram after Ref. 7.)

2. ACCRETION DISKS

Accretion disks on many scales are pervasive in astrophysics. Pre-main sequence objects, such as stars of the T Tauri class or FU Ori stars, present a superb opportunity to study the physics of the disk structure and accretion process. Many young stars are surrounded by disks of dusty material. The presence of circumstellar material, most probably in disk form is repeatedly suggested by different observations: extended emission has been observed directly in the visible, infrared, and radio spectral regions; line profiles of T Tauri stars are consistent with the occultation of re-emitted material by an opaque disk; measurement of an infrared excess by IRAS is believed to signal the presence of dusty circumstellar material. Uniting
reprocessed stellar radiation. Adams, Lada and Shu (Ref. 15) argue that dust must lie close to the central star, yet some stars appear not to be highly reddened, also supporting the presence of disk geometry.

A schematic illustration of a star and disk configuration is shown in Fig. 1. Such a model was developed from study of the spectrum of T Tauri stars over a broad energy range (see Figs. 2 and 3). In these spectra, the optical continuum is typical of a cool star; the infrared continuum is largely optical light reprocessed by the circumstellar disk; and the ultraviolet continuum results from the boundary layer between the disk and the star (Ref. 8). As material in Keplerian rotation in the circumstellar disk (with a velocity \( \approx 200 \text{ km s}^{-1} \)) approaches the slowly rotating stellar surface, this material must dissipate its energy rather rapidly in order for accretion on the stellar surface to take place. This region of dissipation - or boundary layer - produces an ultraviolet continuum that provides the strongest constraint on the accretion rate from the circumstellar disk (Ref. 9).

Kenyon and Hartmann (Ref. 9) argue that the presence of a boundary layer complicates the interpretation of chromospheric spectra from objects such as T Tauri stars. While there undoubtedly is some level of magnetic activity on the surface of these stars that contributes to a typical stellar chromosphere, an additional energy source appears to be required to explain the veiling of photospheric lines in the optical spectrum. The substantial chromospheric radiation that is typical of T Tauri stars (Ref. 4) may result for instance, from enhanced heating of the stellar atmosphere due to the presence of the turbulent boundary layer.

Figure 2. Spectrum of the T Tauri star, BP Tauri, showing the three components contributing to the continuum emission: the boundary layer, the K7 star, and the circumstellar disk. (From Ref. 8.)

Figure 3. Spectrum of the T Tauri star, DL Tauri, showing the contribution of the boundary layer, the star, and the disk to the ultraviolet, optical, and infrared continuum emission. (Adapted from Ref. 8.)
COOL STARS

Figure 4. Schematic drawing of the large scale structure in the atmosphere of the active K-dwarf V471 Tauri. (From Ref. 10.)

Figure 5. Carefully timed short wavelength H/E spectra of the eclipsing system V471 Tauri showing the increasing strength of the absorption features of Si II, O I, Si III, Si IV, and C IV as the white dwarf passes behind the active K-dwarf star. (From Ref. 11.)
Broadly based observations are necessary to understand the physics of the star and surrounding disk. Ultraviolet measurements continue to be crucial to estimate accretion rates. Spectra from these pre-main sequence objects must be interpreted carefully, considering both time dependent effects and non-equilibrium conditions.

3. EXTENDED ATMOSPHERIC STRUCTURES

By analogy with the Sun, we believe that magnetic loop structures must be common on cool dwarf stars, although they cannot be imaged directly. However, by choosing eclipsing stellar systems in which one component is a cool dwarf and the other a white dwarf, Guinan and collaborators (Ref. 10) have been able to discover extended structures in the atmosphere of the cool dwarf star.

One system that has proved to be extremely valuable is V471 Tau, an eclipsing binary in the Hyades with a 12.5 hour period. This system consists of a K2V star and a DA2 white dwarf (see Fig. 4). Photoclectric photometry had revealed that the surface of the K star contained dark spots, and these results were used to select a time of observation when the spots would lie near the limb of the cool dwarf. Low-resolution short wavelength spectra taken with IUE (see Fig. 5), show that absorption features appear as the white dwarf passes behind the lower atmosphere of the K dwarf star at primary eclipse. These features are not present at other times (the white dwarf spectrum is essentially featureless) and particularly, when spots are absent from the stellar limb. These results suggest that the extended atmosphere (the chromosphere and transition region) of the cool dwarf is inhomogeneous, and that the absorption occurs as the light of the white dwarf is absorbed by the hot plasma lying above the spotted regions on the cool dwarf. Because the scale of the system is known, Guinan and colleagues conclude that the hot plasma extends nearly one stellar radius above the surface of the cool dwarf. Parameters of the gas, its electron temperature \( T \approx 10^5 \text{ K} \) and density \( N_e \approx 10^{10} - 10^{11} \text{ cm}^{-3} \), can be estimated from the strength of the absorption lines (see Fig. 5). This gas is not expected to be in hydrostatic equilibrium, and needs to be magnetically supported, much as the solar atmosphere contains magnetically confined material.
Particularly interesting are the large widths of the absorption features. In the Sun, downflows of material are commonly seen; these flows may also be present, perhaps on a greater scale, in the extended structures in the atmosphere of the V471 Tau cool dwarf.

The use of the IUE, with strategically timed observations, demonstrates one advantage of a geosynchronous orbit. These results also make clear the complementary nature of ground and space-based observations to study the magnetic structures in cool stars.

4. PULSATION IN COOL STARS

The longevity of the IUE motivated continuous observations of the star Alpha Orionis (M2 Ia, Betelgeuse). This star was long known to vary irregularly in light, and its brightness made it an easy target on which to obtain high resolution spectra to study the chromosphere and wind. Three years of continuous monitoring both in the ultraviolet and the visible revealed (Ref. 12) that there was a periodic variation in the light of the star (see Fig. 6). A 420-day periodic modulation of the flux is observed in the optical (λ4530) and ultraviolet (λ3000) continua, and in the Mg II (λ2795 and λ2802) line emission cores. There also appears to be a lag in the chromospheric (Mg II) variations as compared to the optical and ultraviolet continua, suggesting that a propagating wave is present in the atmosphere.

Pulsation is the most attractive explanation of these observations since the amplitude of the variation is large, the chromospheric emission correlates well with the continuum behavior as in other pulsating stars such as Cepheids and Mir variables, and the period appears to be appropriate. A fundamental mode of 400 days is predicted (Refs. 10 and 17) for a star with the effective temperature and luminosity of α Ori; the radial velocity amplitude was predicted to be 1-2 km s⁻¹.

A radial velocity variation of ±1 - 2 km s⁻¹ was recently discovered in Alpha Ori (Ref. 18), and the variation is in phase with the published ultraviolet and optical measures (Ref. 12). The period of Alpha Ori appears to be stable through 1987, although with diminished amplitude, and is reported elsewhere in this volume (Ref. 19).

Pulsation has also been recently invoked to explain the anomalous H-α profiles found in metal deficient field giant stars (Ref. 13). These stars show variable emission wings in the H-α lines which are thought to arise in the chromosphere (Ref. 20), and on occasion mass outflow occurs as indicated by a strongly asymmetric line profile (see Fig. 7). Several of the luminous stars of this class, and correspondingly, those on the tip of the asymptotic giant branch, show photometric variability. While no photometric periods have been obtained, the spectroscopic and photometric behavior strongly hints of pulsation processes.

Identification of pulsation in luminous "normal" stars is of great interest to stellar evolution. It is widely recognized that there are certain regions of instability to pulsation across the HR diagram (see, for instance Ref. 21) where stars such as Cepheids, Long Period Variables etc. show strong pulsation. However, accumulating evidence suggests that pulsation may be far more ubiquitous than previously thought.

Pulsation, if it exists, is of particular interest for the problem of driving mass loss from cool stars (see Ref. 22). Luminous cool stars do not have hot coronae, so that the Parker type wind driven by the coronal pressure can not exist. The radiation field of cool stars is not strong enough to accelerate a massive wind as happens in hot luminous stars. Winds driven by radiation pressure on dust grains may be important in the coolest luminous stars, but it is hard to see how dust would form in chromospheric temperatures where emission...
5. MAGNETIC ACTIVITY CYCLES

Our knowledge of activity cycles in cool stars is best known in the Sun, where an “11-year” period in the sunspot number is frequently cited. However careful study (Ref. 23) of the appearance of sunspots over two centuries reveals that the well-known 11 year period can vary from 8 to 15 years; during the Maunder minimum, very few sunspots appeared on the solar disk at all.

One of the goals of contemporary stellar physics is to establish the dependence of surface magnetic activity on macroscopic stellar parameters, for these reveal information about stellar properties difficult to assess from surface observations. The intensity of the emission cores of the chromospheric Ca II lines is frequently used as a proxy for the variation in magnetic activity. This derives from measurements on the solar disk that demonstrate the strong correlation between surface magnetic field and flux in the emission cores of Ca II. Surface magnetic fields are believed to result from the dynamo mechanism whereby subsurface convection and differential rotation regenerate and amplify the stellar magnetic field. Measurement of the dependence of magnetic activity upon stellar mass can then yield information about the properties of the stellar convection zone. The surface rotation rate (and perhaps differential rotation), inferred from the changing pattern of enhancements with time, can constrain the internal differential rotation rate. And the strength of the Ca II emission, defining the chromospheric activity level, reflects an averaged magnetic field strength on the stellar surface.

It has been almost 20 years since the monitoring program in the Ca II lines was first established by Wilson (Ref. 24) at the Mt. Wilson Observatory. This program has been continued on the 60-inch telescope by a consortium of observers (Ref. 25). Some recent
results (Fig. 8, Ref. 14) clearly demonstrate the variety of long term magnetic activity to be found in solar-type stars. Baliunas (Ref. 14) finds that 85 percent of the stars in the sample are variable, and that a period can be derived for about 65 percent of the sample. Study of the dependence of the cycle period on rotation period, mass, or Rossby number reveals no simple dependence on these parameters.

Detailed studies such as these underscore the need for careful continuous measurements of stars, and also raise problems to be addressed by multifrequency observations. For instance, some cycles of smallest amplitudes may be better measured with transitions offering higher contrast than the Ca II lines. The Mg II line is much easier to measure than the Ca II transitions because the contrast with the local continuum is greater. The role of coronas, although small in the total energy budget of an atmosphere, may provide a sensitive way to monitor stellar magnetic activity. The importance of a stellar wind in structuring the outer atmospheres of stars and affecting angular momentum loss has not been evaluated.

Long term, broadly based studies of stars can address new problems in stellar physics, and can also be of great importance in discovering new questions to ask of the more scarce observations from space. In the best of all worlds, a fruitful interchange must be encouraged between ground and space-based measurements.

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IUE Observations and Physical Processes of Interacting Binary Stars

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ABSTRACT
This article reviews some of the physical processes which have been observed in close binary stars, and discusses how IUE observations have contributed to our understanding over the past decade. Processes connected with accretion disk structure and stability, wind accretion and wind - wind collisions, contact systems, and stellar activity are reviewed in "ultraviolet light".

1. Introduction
The study of interacting binary stars was one of the prime objectives of IUE when first proposed as a scientific satellite. At the time, that is in the mid 1970's, there were many questions that needed to be addressed from space. At the time, optimism for understanding interacting binary phenomenology ran high.

Among those working on Algol and related systems a decade ago, it was generally assumed that mass transfer and accretion phenomena would dominate the spectra of these systems in the UV. The presence of disks, indicated from ground based observations by optical emission lines and strong near-ultraviolet continua, seemed sufficient evidence for believing that there would be ample signatures of both mass transfer and mass loss in UV observations of these systems. In addition, the discovery of flaring radio emission from several RS CVn stars, and the observations of radio and x-ray flaring from Algol, pushed thinking in directions that related activity of stars to the presence of nearby companions. However, the understanding at that time of the physical processes associated with such emission phenomena was not complete enough to actually predict much of the UV behavior of interacting binaries.

Here a short digression seems in order. One of the most dramatic discoveries to come out of the operation of IUE is the wealth of plasma phenomenology displayed by stars in general, and binary stars in particular. However, with this discovery comes a fundamental problem, one which could not have been anticipated at the time IUE was designed: To what extent do unique signatures exist for any of the processes one might expect to encounter in mass transferring systems? Unfortunately, the answer appears, at least for the time being, to be that there are no unique signatures, that a hot plasma by any other name is still a hot plasma, and that only the context and the detailed temporal behavior of the individual environment render any plasma medium identifiable among the range of other possible environments. Much of the theoretical work is still to be done in order to understand what we are learning from the ultraviolet observations.

Several recent reviews have appeared dealing with IUE observations of interacting binaries. These include reviews by McCluskey and Sahade (1987), Sahade (1986), and Plavec (1985). This review will deal not so much with the individual observations of specific systems, but rather with the physical processes that can be diagnosed using ultraviolet spectroscopy.

2. Some Basic Aspects of Accretion Disk Theory
Dissipation, of angular momentum and energy, dominates the behavior of plasmas in interacting binary stars. For this reason, and because there has not been too much discussion of the physics of accretion disks in normal systems (as opposed to cataclysmics), we begin with a short review of some of the physics associated with these disks.

An accretion disk is an axisymmetric distribution of matter, circulating about one member of a binary system, whose mass is due to the supply of gas from a companion. The rate of mass transfer onto the accreting star depends on internal processes in the disk, as well as on the rate of supply of matter to the disk, but the amount of mass which will reside in the disk is generally very small compared with the stellar masses. In
fact, it may be the case that only a small fraction of the total mass lost from the companion actually winds up in the disk; much of the material may be lost completely to the system.

The physical picture can be made quantitative through a rather simple theory due principally to Novikov and Thorne (1973) and Shakura and Sunyaev (1973) (see also Pringle (1981); Frank et al. (1985)). We assume that the disk is pressure supported vertically and sending matter slowly inward by viscous dissipation of Keplerian motion. The viscosity is assumed to derive from turbulence and magnetic fields, although this is one of the details that must be examined closely before we can accept this model as a realistic one. This drift - which is assumed for the moment, for the sake of simplicity, to be in steady state - takes place at a rate which depends on the rate of mass loss by the companion:

\[ M = 2\pi \int_{a_0}^{a} \rho(r,z) r \, dz = 2\pi \Sigma o r \]  

where \( r \) is the radial distance from the accreting star, \( \rho \) is the density, \( \Sigma \) is the (vertically integrated) surface density, \( a_0 \) is the radial pressure scale height, \( \rho \) is the mass density, and \( v_s \) is the radial drift velocity. The drift is assumed to transport material inward in response to the outward convection of angular momentum by turbulence. To see this, take the rate of angular momentum loss to be given by:

\[ F = -\frac{1}{\partial t} \rho \omega + \frac{\partial}{\partial r} (\rho v_s \omega) = -\frac{1}{\partial t} \rho \omega = -\rho \sigma_{\phi} \]  

where \( T_{\phi} \) is the stress tensor. It is assumed that the disk is dissipative because of turbulent viscosity, which is also responsible for the angular momentum transfer in the disk which drives the mass accretion. The rate of energy generation in a shearing turbulent medium is given by the stress times the strain, so that:

\[ F = -\frac{1}{\partial t} \rho \omega + \frac{\partial}{\partial r} (\rho v_s \omega) = -\frac{1}{\partial t} \rho \omega = -\rho \sigma_{\phi} \]  

where now \( \sigma_{\phi} \) is the strain tensor for the angular velocity, given by:

\[ \sigma_{\phi} = \frac{\partial \omega}{\partial r}. \]  

The angular velocity is, in principle, something that must be determined self-consistently because of the viscous coupling of the disk to the central star. While this would be important to do in practice, and there have been several attempts in recent years to study this in detail, the simplest physics can be seen by assuming that the disk remains in Keplerian motion. Thus, the strain is proportional to \( \omega \) and the stress is proportional to the local pressure. This latter assumption is the most questionable, but also the one which permits analytic solutions.

The equation of state for the disk governs both the equations for angular momentum conservation and local energy generation through the stress tensor. The simplest prescription is to assume that the shearing stress is proportional to the pressure, an ansatz originally exploited by Shakura and Sunyaev in the so-called \( \alpha \)-disk model:

\[ T_{\phi} = \alpha P \]  

and this is certainly the most crucial assumption of the model. One assumes that \( \alpha \) is constant and in the neighborhood of 0.1 or so (comfortably between very small and unity), and independent of both position in the disk and equation of state.

The viscosity of the disk is taken to be due to fully developed turbulence. Further, one assumes that the transformation of the rotational motion into the stress occurs via the pressure, which is a simple scalar magnitude. The rate of energy generation, which is due to the same processes that are responsible for transporting angular momentum to the disk periphery, becomes:

\[ F = \frac{1}{2} \rho \Sigma \omega (\frac{\partial w}{\partial r})^2 = \frac{1}{3} \alpha z^2 \Sigma (\frac{\partial w}{\partial r})^3 \]  

(see e.g. Bath and Pringle (1981)). Thus, if one assumes that the pressure is determined by the local mass density and temperature, feedback occurs between the rate of energy generation and the vertical structure of the disk.

The vertical structure, assuming that the disk is axisymmetric and planar symmetric, is given by a modified form of the equation for vertical hydrostatic support:

\[ \frac{dP}{dz} = -\frac{\rho M}{r^3} \]  

where the scale height is given by:

\[ z_0 = \frac{a_s}{v_s} \alpha \simeq \left( \frac{RT}{GM\mu} \right)^{1/2} \]  

and \( a_s \) is the isothermal sound speed, \( R \) is the gas constant, and \( \mu \) is the mean molecular weight. The formal solution for the vertical disk structure is:

\[ \rho(r,z) = \rho(r,0) exp \left( \frac{-z}{2z_0} \right)^2 \]  

The vertical temperature gradient is assumed to be due to radiative transfer through an optically thick disk, hence the coupling of the equation of energy generation, which depends on the stress tensor, with the opacity. The depth of the gravitational potential well is very important as well. The equation of state depends on whether the accretor can reach a stage of being radiation dominated, and this feature separates some of the detailed physics of AGNs and collapsed accretors from subdwarf or main sequence stars. The same effect, the heating of the inner disk, feeds back into the stability through the opacity so there is an intimate connection between the physics of energy and angular momentum dissipation and the arrum in which the disks are observed. Finally, depending on the equation of state, the meaning of \( \alpha \) may be changed: it is probable that \( \alpha \) is small in disks which are radiation dominated, and this feature separates some of the detailed physics of AGNs and collapsed accretors from subdwarf or main sequence stars.
prescription for the turbulent viscosity and an improved treatment for the vertical equation of transfer. An analytic treatment of vertical stability for cool $\alpha$ disks has recently appeared (Saio et al. 1987).

In the non-cataclysmic interacting binary stars, the disk dissipation is important for several reasons, even without contributing a substantial luminosity to the system. The first is that the dissipation is responsible for the transport of matter between the components; without the viscous effects in the disk, or (as discussed later) the effects of shocks in the accretion disk, the two stars remain essentially independent. The only effect that the companion would then have would be due to its gravitational influence, and the masses, luminosities and chemical compositions of the stars would remain unchanged by the interaction. The other is that there may be instabilities which are responsible for variations in the spectroscopic characteristics of the stars, even if the photometric properties are immune to the effects of the disk's presence.

Accretion disk instabilities have been studied for some time, but in recent years the interest in cataclysmic and disk variations in AGNs has sparked an intense effort to explain some of the observations is not presently known, but it would be interesting to see whether they can explain some of the quasi-periodic behavior observed in some Be stars with the same efficacy with which they explain the symbiotic stars.

3. Hot Accretion Disk Regions

Early ANS observations by Kondo et al. (1978) showed that in U Cep the ultraviolet variations of the system require hot regions to be present in the surrounding plasma. This conclusion has been supported and extended, using IUE, by Plavec (1983), and Peters and Polidan (1984). The occurrences of high ionization species at discrete phases in the orbits of several binaries, notably W Ser, have shown that considerable dissipation is present in accretion regions, whether these are disks or streams, and that they are not necessarily on the side of the system, at which one would expect the stream to impact.

Peters and Polidan make a most interesting point in their study of CX Dra when, by serendipity, they were able to use an archival spectrum taken only three orbits (8 days) later than their program spectra. The N V line displays considerable variations in profile over just a few orbits, as may some of the other high excitation lines like Si IV and C IV. Evidently, there are other processes at work besides the ones connected with the steady state accretion in these disks. One might speculate that changes in the outer disk structure produce variations in the structure of the region at which the stream from the mass loser intercepts the disk. Such instabilities have yet to be investigated, and must give us pause when considering the models tested with single orbit data or data obtained on several orbits combined to form a single picture of the system. deLoore (1984) remarked that the stability of the disk in $\beta$ Lyr appears to be considerable, since it has lasted for many decades. How well, however, do we really know this? What variations are there in the accretion region structures on timescales longer than a single observing session or shorter than a proposal round?

4. Boundary Layers

The inner region of the accretion disk is dominated by the presence of the stellar surface. Most of the luminosity of the accreting matter is released in a very small radial distance, where the matter slows down to the co-rotating speed of the stellar surface. Although little work has been published during the past decade on this region, the past few years have seen renewed interest in the boundary layer.

In this region the luminosity is given by:

$$L_{BL} \approx \frac{1}{2} \epsilon G M M \frac{c}{R_*}$$

(11)

where $\epsilon$ is the efficiency of the accretion. Most of this luminosity is released in a thin region, which has the temperature given by the virial theorem if it is optically thin:

$$T_{vir} = \frac{3 G M m_p}{8 \pi k R_*}$$

(12)

where $k$ and $m_p$ are the Boltzmann constant and proton mass, respectively. If the boundary layer is optically thick, the temperature can be shown (Shore and King...
1986) to be:

$$T_{BL} = \left(\frac{g M}{3 \pi \sigma}\right)^{1/4} \delta_{BL}^{-1/4}$$

where $\sigma$ is the Stefan-Boltzmann constant, $g$ is the stellar surface gravity, and $\delta_{BL}$ is the geometric thickness of the boundary layer, given by:

$$\delta_{BL} \approx \frac{2}{3} \alpha^{1/2} z_0$$

For main sequence stars of about $3 M_\odot$, the temperature of this region is about $3 \times 10^{6}$K. Possibly the hot plasmas observed in U Sge, R Aqr, and HD 207739 are of this sort.

One consequence of the presence of such a layer is that the UV continuum is stronger than a normal star would have, but the x-ray emission is soft or completely self-absorbed. This means, because of the increase in the scale height of the inner part of the disk, that it may be possible to still observe a substantial UV continuum from the occulted star even during mid-eclipse. This may be the cause of the hot plasma observed in W Ser and the related high mass transfer rate systems.

Recently, fully two-dimensional axisymmetric calculations for boundary layers around white dwarf stars have been performed by Kley and Henkel (1988). These show that the departures from Keplerian motion are approximately correctly predicted by simple $\alpha$-disk models, and that the rate of radiation from this region is significantly lower than expected from the virial calculations. No such models have been calculated for main sequence accretors, and one can only hope that such models will be as successful for interacting binaries as for compact mass accretors. An important observation by Keutsch and Park (1988) shows evidence for non-Keplerian structure in a transient accretion disk in TZZ Eri. They compare this system’s behavior with RW Tau (Plavec and Dobias 1983) and U Cep. A boundary layer or something like it may have been observed in these systems. Stability analyses have been performed recently by Papaloizou and Stanley (1987), Regev (1988), and may be involved with quasi-periodic oscillations of cataclysmic. At present, there is much to be done on the radiative processes involved with more normal accretors.

5. Jets from Accretion Disks

Well known for cataclysmic variables, jets are rare in more “normal” systems. Perhaps the best candidates for jet outflows are several symbiotic stars, notably CH Cyg and R Aqr. The R Aqr jet has actually been observed directly with IUE (Michalitsianos et al. 1986). The excitation appears variable along the jet, and several effects from the Mira have been tried, with highest excitation corresponding roughly to the strongest non-thermal radio component (Kafatos et al. 1986). No variations in the jet lines have been observed. The optical activity of the Mira variable in this system is extraordinary, but its connection with the jet is unclear. A conjecture is that there is a resonance between the period of the Mira variable and a possible eccentric binary orbit, leading to unstable mass transfer (see Edwards and Pringle (1987) for a discussion of models of the effects of eccentricity on mass transfer).

6. Colliding Stellar Winds

Several Wolf-Rayet binaries studied in the past decade display evidence for colliding stellar winds. This problem remains one of the most intriguing hydrodynamic experiments posed by astrophysical systems.

The equilibrium of two winds in collision can be thought of as a stagnation problem with an added twist—material can accelerate away from the line of centers. The first such system to be studied by IUE was HD 47129 (Heap, 1982) for which both components are O supergiants, each being about $55 M_\odot$. Each has a mass loss rate in excess of $10^{-6} M_\odot yr^{-1}$ at a terminal velocity of several thousand km s$^{-1}$. Heap suggested that there was a high excitation region between the stars from which x-rays might be observed and which is responsible for some of the strong line components on C IV and Si IV. Also, this work has not been pursued with any vigor in the past few years. The C IV profile is phase dependent, and suggests that at some phases there may be a high velocity stream which exceeds the terminal velocity of either star.

The suggestion has been made for two WR stars that a wind—wind collision has hollowed out a cavity in the WR star wind. In CQ Cep, Stickland et al. (1984) have noted phase dependent variability of the C IV and N v profiles, which they argue might be the structure of the WR wind. In V444 Cygni, Koeningberger and Aue (1985) first argued, on the basis of the variations of the Fe V lines, that the wind may not be spherically symmetric and Shore and Brown (1988) have produced a model for the colliding winds. In this system, there is a systematic increase in the terminal velocity of C IV and a disappearance of the absorption from the non-resonant He II and N IV lines during the interval within 0.15 around secondary eclipse. These models include the effects of acceleration of the winds by radiation pressure, but neglect the angular momentum of the wind.

In the symbiotic stars, Girard and Wilson (1987) have constructed models of the interaction regions, which they argue may be responsible for the structuring of the circumstellar envelope on long timescales and at large distance from the stars.

7. Wind Accretion

Chapman (1981), Ahmed and Chapman (1986), and Almued and Parsons (1985) have presented evidence for wind accretion in a number of $\zeta$ Aur stars, notably 22 Val. In these models, the wind is assumed to be deflected around the secondary B star, ionized by the radiation field of the star, and an accretion cone is formed on the trailing side of the B star. There is also, in these models, a wake which accompanies the accretion. Some of the observational material is reviewed by Dupree and Reimers (1987), especially from the point of view of late-type, evolved stellar mass loss; a more complete review of the $\zeta$ Aur and related stars is Hack and Stickland (1987).

The most thorough study to date is by Clew-Bolens-Stengel and Reimers (1986). In their study of 31 Cyg, 32 Cyg, $\zeta$ Aur, 22 Val and VV Cep, they conclude that
the wake contributes substantially to the appearance of the emission in the UV spectrum when the system is viewed near secondary eclipse. The opening angle of a supersonic oblique shock is given by:

$$\cot \beta = (M^2 - 1)^{1/2}$$

where the Mach number, $M$, is given by the relative velocity of the accreting star in the wind $v_{ac}/a_s$. For the ζ Aur systems, $\beta < 10^\circ$. Wind temperatures range from about 5000 to 10 000 K and velocities are in the range of 50 to 100 km s$^{-1}$. The observed opening angles are always far greater than this – they argue by as much as a factor of 7 and thus the oblique shock cannot itself be the primary cause for the spectroscopic behavior.

For a gravitational wake, the accretion rate is related to the relative velocity of the star through the wind and the mass of the accretor by $\rho_c M^2 v_{ac}^2$, where $\rho_c$ is the density in the wind in the accretor. Therefore, the rate of mass accretion in the wake of the B star in these systems is given by a simple scaling relation:

$$M_{\text{acc}} = 1.3 \times 10^{-9} m_B^2 \rho_c v_{ac} \approx 10^{-7} M_\odot \text{yr}^{-1}$$

where $v_{orb}$ and $v_{ac}$ are the orbital and wind velocities in km s$^{-1}$, respectively, $m_B$ is the mass of the B star in $M_\odot$, $\rho_c$ is the wind mass loss rate in $10^{-7} M_\odot \text{yr}^{-1}$, and $a$ is the orbital separation in $R_\odot$. The typical accretion rate is $10^{-10} M_\odot \text{yr}^{-1}$, similar to the values derived from the high excitation emission lines observed during the wake presentation (see also Shore et al. 1987).

An additional feature of this model is the formation of an accretion disk around the B star. The radius of the disk is constrained by the fact that it must be larger than the B star and smaller than the radius for accretion of material from the wind of the companion. $R_B < R_{\text{disk}} < R_{\text{acc}}$. The ability of the B star to form an accretion disk depends on the angular momentum carried by the accreting material. For ζ Aur and δ Sge, they find that the disk radius is larger than the B star, while for 32 Cyg it is about the same size. Without allowing for boundary layer effects and the heating that will result in this layer, it is still premature to say that the disk can in fact form. However, it is interesting that the model originally developed for white dwarf accretors in cataclysmic variables can accommodate translation to a more conventional scenario. A model for wind accretion in a hot, massive system, ζ SMC, also appears to require the formation of a wake and disk (Shore, et al. 1987).

This system shows variability of all of the high ionization UV emission lines without accompanying variability of the UV or optical continua. Possible reemission from the accreting material in a boundary layer may be responsible for the time-dependent ionization of the wind from a hypothetical companion. Massive wind-type binaries have also been implicated by Wolf and Stahl and their collaborators as the origin of the variations in several massive supergiants in the Magellanic Clouds. Nussbaumer (1981) has reviewed some of the ionization models for the winds, and Newell and Hjellming have observed directly the structure of the ionized region around α Sco with the VLA. Much remains to be done in other wavelength regions on the stability of the wind structures thusfar discovered with IUE.

8. Mass Transfer

Several reviews have appeared in the past decade on the problem of mass transfer dynamics in binary systems, among the most recent of which is one by Shu and Lubow (1981). This section will briefly summarize some of the basic assumptions and concepts that are important for UV observational studies.

The modelling of mass transfer between components has been focussed on the streaming of material between the stars. Prendergast, in 1969, realized that this can be thought of as a geostrophic flow in which pressure gradients are balanced by the Coriolis effect and the gravitational acceleration, and introduced what has come to be known as Roche coordinates. These make use of the fact that the matter streams in a potential given by the three-body problem, and that equipotential surfaces can be specified exactly so that a cartesian coordinate system centered on the center of mass can be transformed into orthonormal coordinates using $\Phi(\alpha, \beta)$, the gravitational potential for the two stars. The effect of radiation pressure on the mass transfer process is evident even here, since the mass of the luminous star can be replaced, approximately, by an effective mass given by $M(1 - \Gamma)$, where $\Gamma = L/L_{\text{Eddington}}$. One possibility is that the Roche geometry can depend on variations in the stellar luminosity.

Shu and Lubow (1981) review the solutions of the equations of motion for streams in this problem, concentrating on the behavior of matter at three different points in the system: the $L_1$, the point at which the stream intersects the accretion disk, $R_d$, and the $L_3$ point, from which matter can escape from the system.

In the picture developed by Lubow and Shu (1975), mass transfer through the $L_1$ point is much like stellar wind flow. There is a minimum in the width of the equipotential surfaces and a transition between sub- and supersonic flow. The transonic flow results from the vanishing gradient of the gravitational field in the co-rotating frame. The $L_1$ point therefore acts like a de Laval nozzle, with the exception that the Coriolis force breaks the symmetry of the flow and can deviate the resultant stream. The flow thereafter is governed in their model by three-body trajectories which transfer the matter between the components and ultimately either intersect the surface of the companion or form an accretion disk after several shock-irucing intersections of the stream and circulating matter (see Fukue (1987) for a discussion of the disk intersection and some recent references).

Some effects of the Roche geometry have also been noted for wind transfer of mass for Cyg X-1 by Gies and Bolton (1986); a theoretical study has been published by Fried and Castor (1982) that suggests that the wind can be perturbed sufficiently for distorted mass lossers to show some visible spectroscopic effects of streaming. To date, however, these have not been seen unambiguously in the ultraviolet. There may also be substantial...
mass loss from the system as a whole, and as was recog-
nized by many of the earlier modellers of binary stellar
evolution, it is the fraction of orbital angular momen-
tum carried away from the system by the exiting matter
that is central to the subsequent evolution of the binary.
Here IUE has much to offer. By permitting multiple
orbit analysis, by allowing for moderate time resolu-
tion, and by the length of the database in the archives,
one may address questions of structure and evolution in
these systems without the usual horrendous uncertainty
associated with low resolution photometry or (O-C) di-
agram interpretation. It is clear that the direct obser-
vation of velocity fields, such as those of Kondo et al.
(1988) for U Cep for instance, is far more valuable in
placing constraints on the quantitative aspects of mass
loss and angular momentum loss from the system as a
whole.

There has been little direct evidence from IUE for nu-
clear processed matter being transferred from the mass
losing to mass gaining star. Perhaps the best avail-
able evidence comes from the optical study of β Lyr
by Baladi andren et al. (1986) which finds N/C ≈ 9
(solar ≈ 0.2) and N/O ≈ 40 (solar ≈ 0.10); clearly,
the early-type component has been drastically altered.
There is no comparable signature in the UV, in part
because of the effects of stronger absorption from the
gaseous components of the system and in part because
of the greater sensitivity of the lines to stellar wind ef-
tects. This is, nonetheless, an important project for fu-
ture work and one which might be possible using the
IUE archival database.

Several binaries, notably β Lyr, μ Sgr, and ν Sgr
show evidence for mass loss from the outer Lagrangian
point. Parthasanithy et al. (1986) argue that the P
Cygni lines in ν Sgr are formed in the photosphere of
the OB component, not in the common envelope of the
system. There are, however, some lines which may arise
in the common envelope of the system. There is also
evidence for mass transfer from the enhanced CNO abun-
dances in several Algol systems. The prototype mass
transfer system, β Lyr, unfortunately still much the
cigiuna it was 45 years ago, shows ample evidence for
systemic mass loss (Mazzali 1986). The role played by
this mass loss is crucial to the evolution and stability of
the binary, since it is this material which is responsible
for much of the angular momentum loss in the system
which is not tied up in the accretion disk. Furthermore,
it is not clear that an accretion disk even forms in many
of the systems where period changes are observed.

Several recent studies (Sawada et al. 1986, Spruit,
et al. (1987) for instance) have studied the behavior of
the stream - disk interaction region. A most interesting,
though not unexpected, result is that the shocks form a
spiral structure. What is unusual about the Sawada et
al. simulations is that the spiral forms from an initial
accretion ring, and that the transfer of angular momen-
tum outward through the shock can be followed; sub-
sequently, the stream coalesces and forms an accretion
disk. System mass loss occurs mainly through the L2
point, with anywhere from 10 to 80 percent of the mass
lost by the mass loser being lost from the system.

A point at issue is that the accretion and mass trans-
fer in non-cataclysmic systems have different phenom-
ena associated with the streams and disks than when
compact accretors are involved. For one thing, the ac-
creting object is not degenerate and therefore has a dif-
f erent thermal and mechanical timescale. The matter
does not reach very high temperatures, and the Edding-
ton limit does not play a critical role in the structure
of the disk. Further, there may be interactions with the
accreting star due to stellar winds and rotation that
would not normally dominate the structure of an acce-
ration disk in a compact system. Most important, how-
ever, is the fact that the mass gainer is large, physically
disturbed, compared with the size of the binary sys-
tem. The consequence of this is that the stream has a
hard time missing the star, and in general it does not
succeed. Many of the models that have been employed
in the past to interpret the streaming behavior of ma-
terial in binary systems have been designed for none.

LMXRB, and related systems - not for main sequence,
or larger stars. It appears that tidal effects will play
more of a role, the effects of magnetic fields be more
interesting and perhaps important and that pulsation
and boundary layer dissipation will be more important.
Finally, an interesting point recently raised by obser-
vations of Algol (Richards and Bolton 1988, preprint;
Richards 1987, PhD thesis. Toronto) is that the stream
may "flop" in direction through the L1 point. Perhaps
this is due to activity on the cool star passing under
this point in Φ. Such physical processes have yet to be
included in models of these binaries.

9 Contact Systems

Considerable attention has been paid in recent years
to the problem of contact binary stability and structure
(e.g. Mochneki: 1985), with IUE making a valuable
contribution. The discovery of active chromospheres in
these systems is not entirely unexpected, since short pe-
riod, rapidly rotating late-type stars display enhanced
activity indicators. In the past decade, however, with
the simultaneous observations of these systems by EIN-
STEIN, EXOSAT and IUE, it has been possible to make
quantitative statements about the structure of the corona
in a contact system, compared with single stars or other
short period binaries.

Transition region fluxes have been measured by Rucin-
Typically, they are in the same range as the rapidly ro-
ating stars of the same class, about f_xr/f_x ≈ 5 × 10^{-5}
for Si IV + C IV + N V. There appears to be only slight
dependence on the global Rossby number, R_0 = Ωτ_c,
which is a measure of the rotation timescale (given by
Ω^{-1}) compared with the convective turbulent timescale
τ_c (see e.g. Magnesi and Praderic (1984)). This is in
marked contrast to the behavior of the f_xr/f_x accreti-
ion behavior, which is a power law with a lower slope than for
the normal (non-contact) binaries, but which still varies like
log f_xr/f_x ≈ R_0^{0.57}. VW Cep, 44i Boo, and XY Leo,
with periods of 0.27 - 0.29 days among the shortest pe-
riod W UMa stars, have both the highest XR and UV
emission. Vila and Heise (1986) find that for VW Cep, the Mg II H lines vary in phase with the optical light curve, while the EXOSAT 0.1–4 keV continuum varies roughly in phase, but shows considerably more structure than the UV. The X-ray observations of 4IV Boo and W UMa show similar effects.

In the past few years, arguments have been advanced that some of the period changes observed in contact systems, and one of the mechanisms responsible for maintaining contact, may be magnetic in origin. The observation of structured chromospheres and coronae in W UMa systems argues strongly for the presence of surface magnetic activity, in agreement with the waves observed in optical light curves. To date, there is little direct evidence for large surface magnetic fields, in part due to the extremely large rotational smearing that dominates the photospheric line profiles. It is impossible from the UV data to constrain the strength of the surface fields, but the fact that plasma is tied to the stellar surface by the fields is important: the angular momentum loss is proportional to \( J \propto B^{1/2}M^{1/2} \), where \( J \) is the strength of the open magnetic field, averaged over the stellar surface. Mochmacki (1985) has argued that, if the scaling relation used for single stars is employed, the magnetic field \( B \) is given by:

\[
B_p = \frac{B_{\text{sat}} \alpha_p \omega}{B_{\text{sat}} + \alpha_{\text{sat}}} \tag{17}
\]

where \( B_{\text{sat}} \) is the saturation value of the magnetic field and \( \alpha_p \) is an empirical constant. Thus, the enhanced activity of the W UMa stars also increases the rate of angular momentum loss from the system by increasing both the mass loss rate and the field strengths. It would be most interesting to be able to observe the outflow directly; the currently available UV line profiles do not provide sufficient resolution or phase coverage to determine the dynamical structure of the stellar winds.

Finally, a speculation which might be of interest is that some of the dissipation required to explain the light curves of the W UMa systems may be responsible for the generation of chromospheric activity and dynamos in these stars. IUE may be important in placing constraints on non-visible radiative losses from the mass transfer process.

10. Active Chromospheres and Magnetic Field Effects

Considerable attention has been paid to the RS CVn systems during the lifetime of IUE, and it would be difficult to summarize all of this material here (much of it will be dealt with in the papers on cool stars). One physical process that may be best studied in these systems, however, is relevant to the present review: the interaction of magnetic fields among the components of active binary stars.

IUE observations of AR Lac (Neff et al. 1986) show this system to consist of two nearly equal-mass stars, both of which show structured corona indicative of enhanced magnetic activity. In general, the RS CVn systems consist of nearly equal mass stars, both late-type, both of which show some evidence for enhanced dynamo-related magnetic field generation. The interaction of the stars is generally "distant", that is, both components are usually within their Roche lobes. In one system, however, HR 5110, the more evolved star appears to be filling its Roche surface. In RT Lac, the mass ratio is reversed and it appears that this system is in the classical Algol phase of close binary evolution. Since the stars in these binaries have deep convective envelopes, one might expect that the fields would be considerably stronger and more variable than in normal field stars, a discovery which belongs primarily to IUE and which has been the well-spring for an enormous literature (see Jordan and Linsky 1987).

A most interesting set of comparisons is possible using the IUE observations of three close systems, FF Aqr, V471 Tau, and HD 8358. For V471 Tau, Guinan et al. (1986) have observed transient, statistically significant structure in the ingress and egress eclipse light curves in the UV, which they explain by the presence of a loop prominence associated with active regions on the K star. This system is especially interesting in that the white dwarf companion is quite hot and provides a striking analog to the ζ Aur stars for a main sequence system. For FF Aqr, Baltmanns et al. (1986) have found similar behavior. Both are short period systems, with compact or extremely evolved degenerate companions two facts that make them difficult to observe with high time resolution, but excellent systems for probing the atmospheres of unstable stars. These stars permit moderately good coverage of several orbits, and consequently several rotations, of the late-type companion in a few shifts, so it is actually possible to make some statements regarding the stability of the plasma structures observed.

HD 8358 has been observed to have an extremely active and variable chromosphere (Bopp et al. 1985) with strong Hα and Mg II emission and some of the same characteristics as the FK Com stars. The \( f_{\text{ Hin/}f_{\text{ Hα}} \) measured from N V + Si IV + C IV is about \( 3 \times 10^{-4} \), comparable with other very active systems and with the contact binaries already discussed. The \( f_{\text{ Mg II/}f_{\text{ Hα}} \) is about an order of magnitude higher than this. V711 Tau and UX Ari show similar activity levels, but are longer period systems. One point of interest is that HD 8358 has an unusually high space velocity, about 114 km s\(^{-1}\), consistent with it being an old disk or halo population star. While the activity-rotation relation for normal stars, as Bopp et al. point out, is usually interpreted as indicating that young stars show enhanced activity, this system has no high rotation velocity that it may have overridden the influence of age, appearing like a "normal" member of the short period RS CVn group. They also point out that HR 1883, a Pleiades K star, shows similar optical behavior at Hα, although this star is not known presently to be a binary and has not been studied with IUE.

Recently, several studies have focussed on the role that magnetic dynamos may play in affecting the evolution of close binary systems. Van Buren and Young (1983) and more recently Applegate and Patterson (1987)
have remarked on the fact that magnetic activity in the outer convective zones of tidally-locked late-type stars may alter the period of the dynamo timescale. This has also been discussed in a slightly different context by Hall et al. (1980). One of the systems to which this mechanism has been applied is V471 Tau, for which the period changes are probably not merely secular and which has been well studied for almost twenty years.

11. Some Concluding Remarks

This review has concentrated on the ultraviolet portion of the spectrum, and some comparison with ground-based work. Close binaries have, however, been little studied at other wavelength regions. With a few notable exceptions, especially symbiotics, interacting binary systems have not been systematically monitored in the radio or infrared. The multi-wavelength approach has been enormously fruitful in evaluating the importance of different physical processes in shaping the structure of stellar coronae and accretion disks, in cataclysmics and in cool stars. It is certainly time to apply the same approach to interacting binaries. There has been precious little work in the past decade involving simultaneous ground-based optical and IR and radio observations of, for instance, Algol systems with IUE; there is still time to remedy this situation.

What are the most serious questions that IUE in particular, and the past decade of study of interacting binary stars in general, have revealed? For one thing, the time dependent phenomena already known from optical studies appear to be even more important in the ultraviolet. The systems show flows which are unstable on timescales of single orbits, variable winds, tidally-induced phenomena, and unstable stellar components. In order to be sure that we have in fact understood what is going on with these systems, the quick look study is dangerous. In the face of clear evidence that many of the physical processes in interacting binary systems may be nonlinear and highly dependent on the specific details of individual systems, and even on specific times of observation, the reliability of single object analyses and short timescale studies is called into question. We have also learned the hard way that any conservative models for mass transfer between components, steady or otherwise, are simply wrong and need to be corrected in order to properly understand binary star evolution.

It is also important to keep in mind that the interacting close binary of today may be the cataclysmic of tomorrow. As the study of the more normal interacting systems with IUE and other satellites serves to set the stage for the formation of the more extreme hydrodynamic laboratories represented by the collapsed systems.

Furthermore, the lessons being learned from the study of accretion disks around different central objects have invaluable input to the understanding of a wide range of astrophysical environments. It is important to keep in mind that the physics remains the same, only the way in which the equation of state and opacity are tapped by the central gravitational field change when a main sequence star is replaced by, say, a black hole. The central objects in active galactic nuclei are virtually certain to be relativistic and therefore more dominated by radiation processes, and mass accretion rates closer to the Eddington limit than for stellar objects. Nonetheless, many of the processes that take place in such disks may be seen, though in milder form, in stellar type disks. Certainly, we see jets from cataclysmics and from symbiotics. The protostellar disks associated with T Tau and FU Ori objects have been studied in analogy to the hotter stellar disks used for Be stars and symbiotics, and for LMXRBs. There is much to learn from a less parochial approach to both wavelength and mass regime.

It is hoped that a more global approach will eventually be taken to the study of these systems, and when future missions are being planned and future observations being scheduled, the lessons learned from IUE will be taken to heart.

Acknowledgements


This paper is dedicated to the memory of Dr. Frederick Shore.

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Solar System Science
CONTRIBUTED PAPER

IO: IUE OBSERVATIONS OF ITS ATMOSPHERE AND THE PLASMA TORUS


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ABSTRACT

Two of the main components of the atmosphere of Io, neutral oxygen and sulfur, were detected for the first time in 1986 with the IUE. Four observations have yielded brightnesses that are similar, regardless of whether the upstream or the downstream sides of the torus plasma flow around Io is observed. A simple model requires the emissions to be produced by the interaction of O and S atoms in the exospheric range with ~2 eV electrons. Cooling of the 5 eV torus electrons would be required prior to their interaction with the atmosphere of Io. Several inconsistencies in the characteristics of the spectra that cannot be accounted for in this model require further analysis with improved atomic data. The Io plasma torus has been monitored with the IUE since March 1979. This study has established the long-term stability of the warm torus. The observed brightnesses have been analyzed using a model of the torus, and variations of less than 30% in the composition are observed, the quantitative results being model dependent.

Keywords: Io atmosphere, Io torus, Jupiter

1. INTRODUCTION

The products of the active volcanoes discovered by Voyager 1 on Io form a torus of plasma at the orbit of this Jovian satellite. Although the characteristics of the plasma torus are relatively well known, the processes through which it is replenished by Io are not well understood. Most of the volcanic ejecta is not energetic enough to escape Io and thus condense on the surface. However, direct surface sputtering by the torus ions has been found to be an inefficient supply mechanism. As a consequence, an atmosphere has been postulated as an intermediate agent to replenish the torus, but many questions remain unanswered. What is the nature of the atmosphere? Which are the interaction mechanisms between the Io torus plasma and its surface and atmosphere? What is the variability and stability of the system?

Until recently, very few direct observations of Io's atmosphere existed. In 1986, two of the main atmospheric constituents were detected for the first time with the International Ultraviolet Explorer (IUE). The results obtained so far for a total of four such IUE observations are presented in Section 2.

The Io plasma torus has been observed with the IUE since March 1979, when Voyager 1 made in-situ measurements of the torus. A systematic study of the properties and long-term behavior of the torus has since been underway and the most current results of this study are presented in Section 3.

2. THE ATMOSPHERE OF IO

Pioneer 10 discovered an ionosphere on Io, and the Voyager 1 IRIS measured an SO2 surface density < 0.032 cm^2 atm (p ~10^{-7} bars) resulting from either sublimation of SO2 frost or a volcanic plume. At least 20% of the surface of Io is covered by SO2 frost of volcanic origin. The atmosphere could thus be dominated by sublimated SO2 and be collisionally thick or thin, or it could even be episodic, driven by volcanoes. Many models of the atmosphere exist, and some favor a relatively thick atmosphere that can maintain both an ionosphere and an exosphere that could be composed mainly of atomic oxygen and sulfur. Models of this atmosphere, however, as a relatively thick atmosphere that can maintain both an ionosphere and an exosphere that could be composed mainly of atomic oxygen and sulfur. The photochemical products of SO2. Others advocate a thin atmosphere due to the rather limited amount of SO2 surface frost. In any case, neutral oxygen and sulfur are expected to be two of the main atmospheric constituents.

The first detection of emissions of oxygen and sulfur on the atmosphere of Io was made with the IUE in 1986 (Ref. 1). Four short-wavelength (1150 - 1950 Å), low-dispersion spectra (Fig. 1) have been obtained as Io orbited east and west of Jupiter (Fig. 2). Excellent pointing accuracy was maintained throughout the 1.5-hour observations of this moving target, allowing for a positive detection of the emissions. The emissions were found to originate from a region inside ~4 Io radii from the surface.

The observed oxygen and sulfur multiplets are: a blend of OI λ 1304 and SI λ 1299, OI λ 1356, SI λ 1420,
torus plasma flow (at 57 km/sec) around Io, and to the day or night sides. Our observations have viewed both the upstream and the downstream on the day side. The similarity in the spectra obtained should therefore constrain any atmospheric model.

Various spin-forbidden transitions were observed, suggesting electron impact excitation. In fact, the emissions were expected to be produced by the interaction of 5 eV torus electrons with the exosphere. To study this possibility, the emissions were modeled assuming electron-impact as the only excitation process. For sulfur, only the theoretical data of Ho and Henry (Ref. 2) is available, and it includes only three of the observed transitions. From these data, a ratio of the observed emissions was predicted as a function of electron temperature. The measured ratios agree with an electron temperature of \( \approx 2 \text{eV} \) (Fig. 4). The OI \( \lambda 1304 \) electron-impact data has been recently measured in the laboratory by Doering (Ref. 3) to have a resonance near threshold which agrees with that predicted by Rountree and Henry (Ref. 4). The theoretical data of Rountree (Ref. 5) for the OI \( \lambda 1356 \) emission includes another resonance near threshold and was used to model the ratio of these two oxygen emissions as a function of electron temperature. The measured ratio also are compatible with an electron temperature of \( \approx 2 \text{eV} \) (Fig. 5).

The derived column densities, \( 9.4 \times 10^{-14} \text{cm}^{-2} \) and \( 2.4 \times 10^{-14} \text{cm}^{-2} \) for oxygen and sulfur, respectively, are in the exospheric range. Therefore, in this model, an unknown mechanism is required to cool the torus electrons from 5 eV to 2 eV previous to their interaction with the exosphere. One further inconsistency in this model is that resonance scattering of the solar O and S lines was ignored in the analysis because the g-factors are smaller than the excitation rate due to 5 eV electrons, but for emissions produced by 2 eV electrons the excitation rate becomes comparable to the g-factors for some of the multiples.
Although a satisfactory explanation of the IUE observations of the atmosphere of Io cannot be supplied yet, these observations should prove useful in the future as improved atomic data becomes available and more observations are performed. The IUE is valuable for studying Io’s main atmospheric constituents and should thus provide insight into the nature of Io's atmosphere and its interaction with the torus. Future observations should also measure any temporal variations and provide a basis for observations by Galileo and HST.

3. THE IO PLASMA TORUS

The plasma torus is composed primarily of ions of sulfur and oxygen. Its composition is determined mainly by the electron density \( n_e \) and temperature \( T_e \), with average values measured by Voyager 1 of \(-2000 \text{ cm}^3\) and \(~5\text{ eV}\), respectively. The torus has a scale height of about one Jovian radius, and is centered at the orbit of Io with its centrifugal axis tilted \(7°\) away from the Jovian rotational axis. As the plasma coagulates with the Jovian magnetic field, it wobbles with respect to a given line of sight throughout a \(-10\text{ hour Jovian rotation}. A torus ansa at \(~5.9\text{ Jovian radii}, where the column sampled is maximum, was viewed through most of the exposure (Fig. 6). The integration time is typically between \(6\) to \(14\text{ hours and the spectra obtained represent longitudinal averages.} (Ground-based observations of the torus are much shorter and sample the torus longitudinally.)

The observed torus emission features are \(\text{Si} \lambda 1256, \text{SiII} \lambda 1729, \text{and SiV} \lambda 1406\) (Fig. 1), whereas oxygen ions cannot be detected with the IUE. The measured brightnesses vary because of the different viewing geometries, but the ratio of the brightnesses does not vary as much. In order to compare the observations, a model of the torus has to be employed. The original model is described in detail in Skinner (Ref. 8) and Moos et al. (Ref. 9); in this work some model parameters have been updated and the data set has been extended.
The model predicts an average brightness for each of the emission features by estimating the volume emission rate integrated over all the portions of the torus falling in the field-of-view throughout the observation. This volume emission rate is a function of the electron temperature, electron density and ion density and the following representative, longitudinally-averaged spatial profiles for these quantities are adopted:

- the electron temperature and density profiles in the torus centrifugal plane (Fig. 7) derived from the Voyager 1 observations (Ref. 10);
- the electron density at a distance \( z \) from the centrifugal plane approximated with a scaling law (Ref. 11) and using the revised scale height of \( \sim 1 \) Jovian radius (Ref. 12);
- ion densities assumed to be constant fractions of the electron density and to follow the same spatial profile, since the plasma is assumed to be homogeneously mixed; and
- the electron temperature dependence in the volume emission rate is included in the thermally averaged collision strength (Fig. 7) of the \( \text{S} \ II \lambda 1256 \) transition (Ref. 13), but no temperature dependent atomic data is available for the \( \text{S} \ II \lambda 1806 \) emission. Since the atomic data for the \( \text{S} \ II \lambda 1806 \) emission is rather uncertain, the theoretically calculated, temperature-dependent values of Ho and Henry (Ref. 14) have been employed.

The ratio of the measured to model-predicted brightness and the requirement of local plasma neutrality are used to predict the characteristics of the torus plasma, namely the electron concentration relative to the Voyager 1 case, \( R \), and the \( \text{S}^+ \), \( \text{S}^{12} \), and \( \text{S}^{13} \) mixing ratios of fractional concentrations, \( \text{M} \ II, \text{M} \ III, \) and \( \text{M} IV \). The results, presented in Figures 8 and 9, are: \( R = 1.07 \pm 9\% \), \( \text{M} \ II = 0.10 \pm 30\% \), \( \text{M} \ III = 0.22 \pm 17\% \), and \( \text{M} IV = 0.02 \pm 35\% \), plus a mixing ratio of 0.39 inferred for \( \text{O}^+ \). (The large variability of \( \text{M} \ IV \) is partly due to the uncertainty in the low-level \( \text{S} \ II \lambda 1806 \) signal.)
The results indicate that, despite short-term variations of less than \( \pm 30\% \), the torus has remained stable since the Voyager 1 encounter in 1979 through mid-1987. \( \text{S}^{+}, \text{S}^{+2}, \text{S}^{+3}, \) and \( \text{O}^{+} \) would carry respectively 10%, 41%, 67%, and 29% of the charge. These results bring our IUE estimates of the torus plasma charge distribution close to the estimates derived from the in-situ (PlS) plasma measurements and the ultraviolet spectra (UVS) of Voyager 1 as reviewed by Bagenal (Ref. 15). Even though the model cannot distinguish relatively small, simultaneous changes in the electron temperature and density and its quantitative results are thus model dependent, the qualitative result of the long-term stability of the torus is quite firm.

It is important to continue these IUE observations as they constitute a unique, long-term study of torus plasma density and will be an invaluable link between the in-situ measurements of Voyager 1 and those of HST, ASTRO, and Galileo.

We gratefully acknowledge the assistance of the IUE observatory staff in the acquisition and reduction of the satellite data. This research was supported by NASA under grant NGR 53093 to the Johns Hopkins University.

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ON THE ABUNDANCE OF MICRON-SIZED PARTICLES
IN SATURN'S A AND B RINGS

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ABSTRACT
A set of 12 IUE spectra of Saturn's rings was obtained be­
tween July 1982 and February 1985. The large aperture
was positioned on the Cassini division at the western ansa
and the size of the aperture was such that the A and B
rings contributed about equally to the total area inside the
aperture. The IUE data are complemented at wavelength
below 1600 Å by Voyager 2 UVS data. The most obvious
feature of the combined spectrum, which covers the wave­
length range from 500 to 3000 Å, is the water ice absorption
edge between 1000 and 1700 Å. Three different modelling
approaches have been used to interpret the data: 1) Multi­
miple Rayleigh scattering approximation for extremely small
particles (r ~ 0.003 μm), 2) Single Mie scattering for power
law size distributions (0.01 μm < r < 40 μm), 3) Hapke ge­
omechanical optics approximation for very large ring particles
(r > 100 μm). The most satisfactory fits can be obtained
with the Mie scattering approach and the Hapke approx­
imation. However, the available data are not sufficient to
uniquely determine a particle size distribution.

II. DATA
Saturn's rings were observed between July 1982 and Feb­
uary 1985 in 12 exposures ranging in duration from 20 sec to
5.5 h (Table 1). The large aperture of the IUE was centered
on the Cassini division in the west lobe by offsetting from
Titan (Fig. 1). The opening angle of the rings increased
from 10° in 1982 to 23° in 1985. All data were normalized
to the 1985 spectrum. Average reflectivities were calcula­
ted using the projected area of the A and B ring inside
the aperture and the 1982 solar spectrum of Mount and
Rottman (Ref. 3, 4).

Table 1.
SUMMARY OF OBSERVATIONS OF SATURN'S RINGS

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<th>Image number</th>
<th>Date</th>
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<th>B</th>
<th>B'</th>
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<td>900</td>
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</table>

1° = solar obsidian latitude of the Earth
B' = solar obsidian latitude of the Sun
Ω = Solid angle of A and B ring inside the large aperture

Fig. 2 shows the IUE data together with complementary
data from the Voyager UVS experiment, reduced to the
same scale as the IUE data by Geissler and Høiberg (Ref. 5).
The Voyager 2 data were obtained in 1981 when the sat­
urnicentric latitude of the Sun was 8°. The projected slit of
the UVS covered parts of the A ring but mainly the B ring.

The derived column abundances of $N_{\text{ice}} = 6 \times 10^{15}$ cm$^{-2}$ and $N_{\text{vapor}} = 3 \times 10^{14}$ cm$^{-2}$ have to be considered upper limits only, because the effect of the larger ice particles was completely ignored in this calculation.

b. Mie scattering ($1 < x < 30$)

In this regime the phase function varies strongly with $x$ and with the optical constants and is therefore a complicated function of the wavelength. The best approximation in this size range is given by the Mie scattering phase functions for spherical particles.

Since all of our ring observations were obtained near a phase angle of 6°, the calculations are limited to single scattering with a scattering angle of 174° to facilitate the exploration of the particle size distribution parameter space. The phase function for multiple scattering is assumed to be isotropic and the radiative transfer equation is solved using the two-stream approximation (Ref. 7).

For the Mie scattering calculations we use a power law particle size distribution of the form

$$N(r) = \text{constant} \cdot r^q.$$  

Such a distribution has three adjustable parameters: the minimum and maximum radius $r_{\text{min}}$, $r_{\text{max}}$ and the power law index $q$.

Because the Mie scattering calculations become prohibitively expensive in terms of computer time for very large particles ($x > 1000$) the maximum size cutoff was chosen to be fixed at $r_{\text{max}} = 40 \mu m$. Since the contributions of large particles to the backscattered light are very important for power law indices of $-1 < q < -2$, a power law representation of the particle size distribution will be very sensitive to $r_{\text{max}}$.

The optical constants of H$_2$O-ice are taken from the compilation of Warren (Ref. 8). The steep rise of ring reflectivity from the UV to 6500 Å indicates that the rings cannot consist of pure water ice alone. To estimate the effect of any "dirt" in the ice on our calculations we modified the imaginary part of the index of refraction of pure H$_2$O-ice by adding a constant $k_f$. So that our Mie scattering models of the singly scattered intensity at a scattering angle of 174° is parameterized by $q$, $r_{\text{max}}$, and $k_f$.

The Mie scattering coefficients are calculated with a program based on the BHMIE code of Bohren and Huffman (Ref. 9). For unpolarized incident light the scattered irradiance $I_s$ is related to the incident irradiance $I_i$ by

$$I_s = \frac{S_{11}}{2} I_i,$$

where $x = 2\pi r/\lambda$ and $S_{11}$ is an element of the Stokes scattering matrix and depends on the scattering angle $\theta$ and the particle radius $r$. For each particle size the phase function at a scattering angle $\theta$ is given by

$$p_{\text{r}}(\theta) = \frac{4 S_{11}(\theta)}{Q_{\text{sec}} \pi^2},$$

where $Q_{\text{sec}} = \sigma_{\text{sec}}/\pi r^2$ is the scattering efficiency factor and $\sigma_{\text{sec}}$ the scattering cross section. The normalization of the phase function was chosen such that

$$2\pi \int_0^\pi p(\theta, r) \sin(\theta) d\theta = 1.$$  

This range of particle sizes was assumed to overlay the bulk ring material in our first attempt at analyzing these data (Ref. 6). The models consisted of two layers. The top one contained small Rayleigh scattering H$_2$O-ice particles with an effective particle size of 0.003 μm and some H$_2$O-vapor as well. The bottom layer consisted of an isotropically scattering absorber.
The single scattering albedo for each particle size $\omega_r$ is defined by

$$\omega_r = \frac{Q_{\text{scat}}}{Q_{\text{ext}}}$$

as the ratio between the scattering and total extinction efficiencies.

Average phase functions and single scattering albedos are calculated using $S_{11}$ as weights

$$p = \frac{\int_{r_{\text{min}}}^{r_{\text{max}}} p(r) S_{11}(r) \, dr}{\int_{r_{\text{min}}}^{r_{\text{max}}} S_{11}(r) \, dr}$$

and

$$\omega = \frac{\int_{r_{\text{min}}}^{r_{\text{max}}} \omega(r) S_{11}(r) \, dr}{\int_{r_{\text{min}}}^{r_{\text{max}}} S_{11}(r) \, dr}.$$  

The integration is performed using the cubic spline interpolation method. Since the scattering coefficient $S_{11}$ oscillates very rapidly as a function of $r$ for large particles and $k < 10^{-3}$ (i.e., $\lambda > 1750 \, \text{Å}$), the integration steps in particle size have to be very small. All of the calculations presented here used step sizes between 0.02 and 0.05 $\mu$m.

Examples of typical results are shown in Figures 3a and 3b for a power law index $q = -2$, minimum size $r_{\text{min}} = 3 \, \mu$m, and three different values of the added imaginary refractive index ($k_f = 10^{-4}$, $10^{-5}$, and $10^{-6}$). Increasing $k_f$ reduces the step in both $\omega(\lambda)$ and $p(\lambda)$ from low values shortward of 1650 $\, \text{Å}$ to high values longward of 1700 $\, \text{Å}$. Values of $k_f < 10^{-6}$ have no influence on the results. The phase functions (Fig. 3b) show some residual fluctuations near 1900 $\, \text{Å}$ due to the finite step size in the integrals over the size distribution (in this case $\Delta r = 0.07 \, \mu$m).

The results of the Mie scattering calculations $\omega$ and $p$ are then substituted into the equation for the radiance factor $I/F$ from Hapke’s bidirectional reflectance theory (Ref. 7):

$$I/F = \pi \omega \frac{\mu_0}{\mu + \mu} [p + H(\mu_0)H(\mu) - 1],$$

where $\mu_0 = \sin(\beta') = 0.386, \mu = \sin(\beta) = 0.404$, and Chandrasekhar’s $H$-function is approximated by

$$H(\mu) = \frac{1 + 2\mu}{1 + 2\mu\sqrt{1 - \omega}}.$$  

Shadowing and opposition effects have been ignored, and the theory implicitly assumes a semi-infinite homogeneous layer. Furthermore, multiply scattered radiation is assumed to scatter isotropically.

To compare the model $I/F$ values with the data in Fig. 2, the models are normalized by a factor (typically $\sim 0.3$) that minimizes the deviations. The simplifying assumptions mentioned in the previous paragraph are responsible for the much higher model reflectivities compared to the data. It is assumed, however, that these simplifications introduce systematic errors that are independent of wavelength, so that the following comparison is still meaningful.

The first set of models shown in Fig. 4a were calculated with $k_f = 0$, $r_{\text{min}} = 1 \, \mu$m, and three different values for the power law index $q$. A systematic trend is apparent. The absorption edge moves toward shorter wavelength as the power law gets steeper.

In Fig. 4b three models are shown with different values of $r_{\text{min}}$, and fixed values of $k_f = 0$, and $q = -2$. Here the shape of the absorption edge varies slightly, but the net effect is a shift of the edge toward shorter wavelength for decreasing $r_{\text{min}}$.

Fig. 4a and 4b seem to imply that a satisfactory fit to any chosen power law index could be obtained by adjusting $r_{\text{min}}$. This was found to be true for power law indices between $q = -2$ and $q = -3.4$ and presumably steeper ones as well. However, for $q = -1$ even and $r_{\text{min}}$ as small as 0.005 $\mu$m did not yield a good fit. Well fitting combinations of $q$ and $r_{\text{min}}$ in the case of $k_f = 0$ were $q = -3.4, r_{\text{min}} = 2 \, \mu$m, and $q = -2, r_{\text{min}} = 0.7 \, \mu$m.

Increasing $k_f$ to values above $10^{-6}$ had the effect of raising the required $r_{\text{min}}$ for a given $q$, and decreasing the step across the absorption edge. One of the best fits, shown in Fig. 5, was obtained with $k_f = 10^{-5}, q = -2$, and $r_{\text{min}} = 2 \, \mu$m. However, values of $k_f > 10^{-4}$ are inconsistent with the data.

c. Geometrical Optics ($z > 30$)

Exploratory calculations were performed using the geometrical optics analysis of the scattering of large, irregular particles by Hapke (Ref. 7). It contains a free parameter $a$ [the internal scattering coefficient, due to inhomogeneities or inclusions in the ice particles, and the H$_2$O-ice optical constants were modified as above by adding $k_f$ to the imaginary refractive index].
The absorption edge in the spectrum of Saturn's Rings can be reproduced with $k_f < 10^{-4}$ as above, and $s \sim 1 \mu m^{-1}$. The results are rather insensitive to the particle size distribution.

**IV. DISCUSSION**

The present detailed analysis of the UV scattering and absorption characteristics of $H_2O$-ice particles indicates that spectroscopic observations alone are not sufficient to determine the particle size distribution in Saturn's rings. The analysis indicates that the spectrum is dominated by large particles ($r > 1 \mu m$), although the presence of significant amounts of submicron-sized particles cannot be precluded.

A rather firm conclusion is that the "dirt" in the $H_2O$-ice contributes about $10^{-5}$ to the average imaginary refractive index but no more than $10^{-4}$.

**ACKNOWLEDGMENTS**

We thank the staff of the IUE observatory for their assistance during the observations. T. Y. Brooke provided the Mie scattering routine and helpful insights from his work on IR scattering properties of large particles in comets. Thanks to P. E. Geissler and J. B. Holberg for providing us with the UVS data prior to publication.

**REFERENCES**

JOVIAN EQUATORIAL H$_2$ EMISSION FROM 1979–1987

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ABSTRACT

Ninety two IUE observations of the Jovian equatorial region taken by Johns Hopkins University observers between 2 Dec 1978 and 1 Feb 1988 were averaged together by date of observation, resulting in 22 averaged spectra which were fit with a model to determine the amount of H$_2$ Lyman band emission in the region 1552–1624 Å. The data suggest that the H$_2$ emission may vary with time. Especially suggestive is the marked downward trend of the emission between 1983 and 1987, during which time the strength of the emission in the 1552–1624 Å region decreased by about a factor of 10. Uncertainty in the existing data and a gap in the data in 1980 and 1981 preclude a positive identification of a correlation between the brightness of the H$_2$ emission and the major solar cycle.

INTRODUCTION

Molecular hydrogen emission from Jupiter's atmosphere was first detected in the Lyman bands of the Rydberg band systems by sounding rocket experiments in the early 1970s (Refs. 1, 2). Positive identification of the Werner bands was not made until the Voyager 1 flyby (Ref. 3) when two distinct phenomena were also identified: intense emission confined to the northern and southern auroral ovals and diffuse emission uniformly distributed over the sunlit hemisphere of the planet and not apparently connected with auroral activity (Ref. 4). The same distinct phenomena were subsequently observed by Voyager 1 on Saturn and Uranus (Refs. 5, 6). The most obvious source for the diffuse UV emissions is photoelectron excitation of H$_2$, the predominant constituent of the atmospheres of Jupiter, Saturn and Uranus. However, the intensity of the diffuse emissions on all three of these planets is much higher than that predicted by calculations of the solar energy input into the atmosphere via photoelectron excitation of H$_2$. The discrepancy on Jupiter and Saturn is about a factor of 5 and on Uranus about a factor of 15 (Ref. 7). Although the emission must be triggered by solar photons because it is only seen in the dayside atmosphere, the energy for the emission process must be produced locally in the atmosphere (Ref. 8). Because the origin of the diffuse emissions is unknown, yet is common to the three outer planets visited by Voyager 1 to date, Broadfoot et al. (Ref. 6) coined a new term, "electroglow", to describe this unexplained phenomenon.

Several different explanations for the electroglow have been put forward (Refs. 7, 8, 9, 10). Since all theories depend on some process which is triggered by solar energy input, the relationship of electroglow to the major solar cycle is "a matter of vital interest" (Ref. 9). Reanalysis of early observations of Jovian atmospheric emissions by Shemansky and Judge (Ref. 11) showed relatively little variation in the disk-averaged (that is, auroral plus diffuse) H$_2$ band emission compared to a large variation in the H I Ly$\alpha$ emission brightness between 1972 and 1979. Nine years (1979–1987) of virtually continuous observations of the Jovian atmospheric emissions with the International Ultraviolet Explorer (IUE) satellite spanning solar cycle 21 (with maximum in ~1980 and minimum in ~1985) are also available for such an analysis. Skinner et al. (Ref. 12) used this database to show that the (non-auroral) Jovian H I Ly$\alpha$ emission brightness varied with the long-term solar Ly$\alpha$ output, decreasing by a factor of ~2 over the time period covered by the observations. However, as can be seen from Fig. 1, the
H₂ band emission signal is very weak and not easily separated from the background, in sharp contrast to the very strong Lyα emission, which is easily measured.

In the short wavelength region covered by the IUE (≈1150-1900 Å) the H₂ Werner band emission, which is detected from ≈1240-1280 Å, is weaker than the detectable Lyman band emission (≈1550-1620 Å) and therefore subject to large uncertainty due to background subtraction problems. Unfortunately, although the Lyman band signal is stronger, it lies in a region of the spectrum where the solar continuum and the albedo of the planet rise sharply (see Fig. 2), making an accurate subtraction of the background level difficult. A previous analysis by Coplin (Ref. 13) used a least squares method in which a model spectrum composed of the 1552-1624 Å region of a bright Jovian north pole auroral spectrum and an assumed linear background was fit to the corresponding region of 21 equatorial spectra to determine the intensity of the H₂ Lyman band emission (a₂) in the 1552-1624 Å region. The results of the Coplin analysis were consistent with a constant level of emission of ~1 kR over the period 1982-1986. A very rough division of the spectra into two 180° longitude bins showed no enhancement in the H₂ Lyman band emission corresponding to that observed in the Lyα emission (the so-called Lyα "bulge"), tentatively confirming the Voyager 1 detection of no significant enhancement in bulge to non-bulge emission for H₂.

One of the most serious uncertainties in the Coplin analysis was the assumption of a linear background over the region of the Lyman band emission. In addition, observations made between 1978 and 1981 (and observations subsequent to the Coplin study, 1987 present) were not included in the analysis. Presented below is a more sophisticated determination of the background which has been substituted for the linear one used in the Coplin model. The H₂ emission from the expanded data set was then evaluated using the same least squares analysis as that of Coplin to determine the variation with time (if any) of the H₂ Lyman band emission in the 1552-1624 Å region.

For our purposes the observed flux in an IUE spectrum of Jupiter can be thought of as simply

\[
\text{Observed flux}(\lambda) = \text{Background}(\lambda) + H_2 \text{ emission}(\lambda)
\]

was fit to the corresponding region of 21 equatorial spectra to determine the intensity of the H₂ Lyman band emission (a₂) in the 1552-1624 Å region. The results of the Coplin analysis were consistent with a constant level of emission of ~1 kR over the period 1982-1986. A very rough division of the spectra into two 180° longitude bins showed no enhancement in the H₂ Lyman band emission corresponding to that observed in the Lyα emission (the so-called Lyα "bulge"), tentatively confirming the Voyager 1 detection of no significant enhancement in bulge to non-bulge emission for H₂.

\[
\text{Model}(\lambda) = a_0 + a_1 \lambda + a_2 * \text{auroral flux}(\lambda)
\]

where

\[
\omega = \text{IUE slit size}
\]

\[
R_J = \text{sun-Jupiter distance in AU (5.203 AU)}
\]

\[
A(\lambda) = \text{the albedo of Jupiter}
\]

\[
F_0(\lambda) = \text{the solar flux measured at the earth}
\]
Note that the shape of the background with wavelength is determined by the solar flux incident on Jupiter's atmosphere and the amount of the incident flux which is "reflected" by the atmosphere (the albedo). The albedo is determined by the major constituents of Jupiter's atmosphere, namely H₂ and He, which scatter the incident radiation, and hydrocarbons such as acetylene (C₂H₂) and ethane (C₂H₆), which absorb the incident solar flux. We use a theoretical model of the Jovian albedo by Gladstone and Yung (Ref. 11 model #2) which is based on a homogeneous atmosphere with constant mixing ratios of H₂ = 0.89, He = 0.1, C₂H₂ = 1.4 × 10⁻⁷, C₂H₆ = 6.5 × 10⁻⁶, C₄H₂ (diacetylene) = 2.6 × 10⁻¹⁰, and C₂H₄ (ethylene) = 1.9 × 10⁻¹⁰. This model is known to match a typical equatorial H₂E spectrum well over the wavelength range 1500-1750 Å. The background is computed at 1 Å intervals and then smoothed to H₂E resolution (~10 Å). The model albedo, solar flux (scaled) and the resulting "background" used in determining the H₂ emission are shown in Fig. 2. Note that the small scale features (~10 Å) come mainly from the solar spectrum, whereas the general rise in the background over the region of the Lyman band emission is determined by the albedo.

With the improved background determination, the model used in the least squares fit to the data becomes

\[ \text{Model}(\lambda) = a_0 + R(\lambda) + a_2 + \text{auroral flux}(\lambda) \]

The 1552-1624 Å region of a typical spectrum and the fit to the data are shown in Fig. 3.

---

**Fig. 2.** Model albedo, solar flux and resulting background

**Fig. 3.** Fit to data in the 1552-1624 Å region.
RESULTS

Ninety-two IUE observations of the Jovian equatorial region by Johns Hopkins University observers taken between 2 Dec 1978 and 1 Feb 1988 were averaged together by date of observation, resulting in 22 averaged spectra, which were then fit with the model described above to determine the amount of \( \text{H}_2 \) Lyman band emission in the region 1552–1621 Å. The results of this analysis are shown in Fig. 1.

Although still preliminary, the data suggest that the \( \text{H}_2 \) emission in this region may vary with time. Especially suggestive is the marked downward trend of the emission between 1983, when the \( \text{H}_2 \) 1552–1621 Å Lyman band brightness was \( \sim 1 \text{ kR} \), and mid-1987, when it was \( \sim 0.1 \text{ kR} \). The low emission in 1978/79 and late 1981, 82, and 83, and the lack of data in 1980 and 81 preclude an unambiguous identification of a correlation between the \( \text{H}_2 \) emission and the major solar cycle. However, note that the late 1982 and 83 data points also have the largest uncertainties. The addition of data from observers other than those at Johns Hopkins, as well as analysis of the \( \text{H}_2 \) Werner bands continues and may allow more definitive conclusions to be drawn in the near future.

Acknowledgments. M. McGrath wishes to thank D. Strobel, W. McMillan, R. Gladstone, and R. Yelle for their helpful discussions. We gratefully acknowledge the help of the National Space Science Data Center at NASA/Goddard Space Flight Center, in particular C. M. Perry, in obtaining image files for the early IUE observations via the SPAN network. This work has been supported by NASA grant NSG5393.

References


Fig. 4.
LARGE TIME SCALE VARIATION IN HYDROGEN EMISSION FROM JUPITER AND SATURN

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ABSTRACT

IUE and Voyager spacecraft observations of Jupiter and Saturn have been combined to obtain a consistent measurement of temporal variation of the equatorial subsolar hydrogen emission. The outer planet systems appear to have rather independent behavior over time scales of the order of 10 years, particularly in emission from the H Lyα line. The time interval from 1978 to the present shows variation of mean equatorial H Lyα brightness of ~2 at Jupiter and ~5 at Saturn. The relative magnitudes of the variations are sufficiently different to suggest that responses to input from the sun is at least nonlinear. The brightness of H₂ band emission appears to be relatively more stable than H Lyα. There is evidence in IUE observations of a moderate increase in H₂ band brightness with increasing time at Jupiter, in opposition to the variation in H Lyα.

Keywords: Solar system/atmospheres

1. INTRODUCTION

Emission from atomic and molecular hydrogen is an understandably dominant feature in the EUV spectra of the outer planets, particularly on the sunlit hemispheres. A current question of high interest involves the fundamental issue of exactly what process produces electronically excited states in the gas to generate the observed emission. The auroral emissions are certainly produced by particle precipitation, but the prominent emissions from the sunlit equatorial regions are spatially diffuse and the interpretation of how the gas is excited is less obvious. The strong emission of the H₂ Rydberg band systems has been interpreted as primarily collisionally induced by electrons (see Ref. 1). This conclusion was based on the fact that an electron excited model accurately matches the spectrum and on the estimation that fluorescence of solar radiation should be very weak. However, more recently (Ref. 2) it has been suggested that fluorescence may play a more dominant role in the excitation process through application of a model using a brighter solar EUV source and converting most of the flux into fluorescence. The difference between these conclusions has significant implications for the energetics of the atmosphere. If the source is dominantly electron excitation, the relatively high temperatures at the top of the thermospheres of Jupiter, Saturn and Uranus could be explained by heating produced as an intrinsic part of the process (Ref. 3). Some other explanation of the thermal structures would have to be found if the fluorescence process dominated.

We describe below an analysis of observations obtained at the Voyager spacecraft encounters in combination with the long time line of measurements provided by the IUE satellite. We find that although the interpretation of the H Lyα emission in terms of atmospheric excitation processes is more difficult, the observed temporal variations are very distinctive, and planet to planet variations are also evident. The results appear not to be compatible with an atmosphere responding only to the deposition of solar radiation.

2. ANALYSIS OF OBSERVATIONAL DATA

Several factors affect the data reduction process particularly in the extraction of the planetary emission rate of H Lyα (1216 Å) from the observed spectrum. The measured signal at 1216 Å includes H Lyα emission in varying amounts from the local geocorona, emission from the local interstellar medium (LISM) along the line of sight to the planet, and in the case of Saturn a portion of the SWP large aperture includes emission along the line of sight beyond the location of the planet. The effect of extinction of the H Lyα signal from the planet is also significant for Saturn in particular. All of these effects were accounted for in the analysis through the use of a geocoronal model developed in this program, and a model of the LISM (Ref. 4).

Most of the IUE SWP spectra of Saturn were reduced in a line by line analysis of the image in order to obtain uncontaminated measurements of the equatorial region.

2.1 Jupiter

The H Lyα emission from Jupiter's equatorial region shows two separable temporal characteristics. The bulge phenomenon associated with a broad magnetic longitude region (~125° FWHM) with enhanced emission centered on 110° LIM. The results obtained in the current observational program and earlier analyses show that the phenomenon is always present and has persisted with approximately the same amplitude since 1979 (Refs. 1, 5). Figure 1 shows data from August 1984, April 1985, and November 1986 as a function of central meridian longitude (CML) obtained from the current observational program. The amplitude and general shape and location of the CML modulation is essentially unchanged from results derived from earlier observations (Refs. 6, 7, 1, 5). The data in Figure 1 shows an emission peak near 105° CML and a minimum near 200° CML. The consistency in location shows that the phenomenon is defined in an absolute sense by CML magnetic longitude. The magnitude of the modulation according to the IUE data shown here and the results reported by Ref. 5, suggests some variability. The mean modulation shown in Figure 1 is ~1.45 in peak to trough ratio. Values reported by Ref. 5, vary from 1.7 to 1.05 with no clear long
### Table 3

Rough estimate of extinction by the ISM/ISM for observations of H Ly-α

<table>
<thead>
<tr>
<th>Obs. Date</th>
<th>[I(H Ly-α)°°]</th>
<th>[I(H Ly-α)]°°</th>
<th>λ°°</th>
<th>CML</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocket</td>
<td>1972/144</td>
<td>1.5</td>
<td>1.6</td>
<td>0.51</td>
</tr>
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<td>1978/355</td>
<td>1.9</td>
<td>2.1</td>
<td>0.11</td>
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<td>1979/187</td>
<td>22</td>
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<td>7.2</td>
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<td>12</td>
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<tr>
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<td>1985/99</td>
<td>6</td>
<td>0.16</td>
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### Table 2

1986 DOY 252 and 254 SATURN IUE OBSERVATIONS OF H Ly-α

<table>
<thead>
<tr>
<th>SWP</th>
<th>Exposure Duration (Min)</th>
<th>Scattering Background (BP/S)</th>
<th>I Ly-α Observed (KR)</th>
<th>I Ly-α Geocorona (KR)</th>
<th>I Ly-α ISM a (KR)</th>
<th>I Ly-α a b Saturn Emission (KR)</th>
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<tr>
<td>29170</td>
<td>30</td>
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<td>0.632</td>
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<td>15</td>
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<td>2.532</td>
<td>1.220</td>
<td>0.508</td>
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<tr>
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<td>1.813</td>
<td>0.625</td>
<td>0.508</td>
<td>0.989</td>
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</table>

a) Sky Background Observation (60° N of Saturn)  
b) Expanded Saturn Emission = [I(Hα)Obs - IGeocorona]/.72  
c) I Ly-α/ISM = [I(HLy-α)°° + ISM/ISMcorr]/.72  
I(HLy-α)°° = 0.622 KR  
I(ISM/ISMcorr) = 0.463 KR

### References

[3] In Table 3, the authors should use "Meteoroid Rustification Index Solar" instead of "Solar."
term trend.

The long term variation of the Jupiter H Lyα emission is shown in Figure 2, which combines results from Voyager and IUE for the outer planets. The variation of the anti-bulge emission rate over the time period 1979-1987 is approximately a factor of 2, in agreement with the results recently reported by Ref. 5. The IUE measurements of Jupiter are corrected for extinction by the LISM; the extinction effect for Jupiter H Lyα is expected to be small, but may account for the slightly larger Voyager values. Extinction of the H Lyα line has also been corrected in the analysis of the Saturn and Uranus data as described below.

The IUE SWP system is the only experimental system currently capable of providing measurements of the H Lyman and Werner Rydberg bands in the equatorial region. The total brightness of the H Lyα bands (Lyman + Werner, I(H Lyα+Lyα)) is estimated by comparison with model calculations (see Ref. 1). Brightness values for various observations, including rocket and Voyager data, are compiled in Table 1. The values for I(H Lyα+Lyα) obtained from the IUE data tend to be larger than the earlier Voyager and rocket data (Table 1, see Ref. 7). However, uncertainty in the measured quantities overlap the earlier results and the results derived here from the more recent IUE data, particularly near the end of 1986 (Table 1), indicate that the H Lyman and Werner bands were as bright or brighter at solar minimum as they were near solar maximum in 1979.

Table 1 includes the measured differential brightness at 1600 Å, which represents the reflection of solar continuum radiation near the homopause. This region of the solar spectrum is essentially constant in absolute flux compared to the temporal variability of the shorter wavelength radiation. The various measurements of this quantity obtained from 1972-1987 (Table 1) show that within measurement error the equatorial subsolar flux at 1600 Å is constant (see Ref. 7). The comparison of the results from the different experiments at 1600 Å provides confidence in the absolute calibrations.

2.2 Saturn

Analysis of the equatorial emission spectra of Saturn is restricted to the determination of H Lyα brightness and the solar reflection continuum at 1600 Å. The factors affecting the determination of the H Lyα brightness as discussed above, are more critical at Saturn than Jupiter because of the greater distance to the planet combined with weaker source rates. Table 2 shows the sequence of observations with the measured H Lyα intensity in column 4. Interpersed with the Saturn observations are background data obtained 60° north of the planet. These background data may contain contributions from the Saturn corona (Ref. 3) but we have not attempted to remove this component from the analysis due to lack of a reference point. This problem will be corrected in subsequent observations. Background is composed of geocoronal and LISM components as estimated in column 5 and 6 of Table 2. The data also contain a foreground component from the Saturn corona, but none of the reported observations including the Voyager results (Refs. 8, 2, 3) are corrected for this contribution. Although the observed emission brightness varied from ~ 3.1 kR to ~ 1.8 kR during the sequence, most of the variation appears to be caused by the geocoronal component, and the derived Saturn emission brightness is basically constant during the sequence with an estimated mean value of 1 H Lyα = 0.8 ± 0.2 kR (Table 2). The geometry for the 1986 DOY 252,254, observations is ideal in the sense that the planet is essentially directly upstream from the earth relative to the bulk flow of the LISM, so that extinction of the planetary signal is at a minimum. However, the observing geometry at the time of the Ref. 9 observations indicates a substantially larger extinction factor. Estimates of the extinction coefficient are given in Table 3. The coefficient has been normalized by analyzing the IUE data obtained near the time of Voyager encounters in 1980 and 1981. As shown in Figure 2, the H Lyα line according to the combined Voyager and IUE data, declined significantly by a factor of about 5, between November 1980 and August 1986. The Voyager data above indicates a reduction by a factor of 1.7 in the ~ 1 year interval between encounters, a period in which the solar H Lyα line showed no significant long term variation.

3. DISCUSSION AND CONCLUSIONS

The rather independent behavior of the three outer planets in relation to each other and to the major solar cycle indicated in the results compiled here for H Lyα subisolar emission rates suggests that the responses of the atmospheres to solar radiative energy deposition is substantially decoupled or at least very nonlinear. Jupiter shows a long term trend from solar maximum to solar minimum of a factor of about 2 comparable to the variation of the solar H Lyα flux. In the same period, the Saturn emission rate declined by a factor of 5. Uranus, according to the Ref. 9 results shows no particular trend from 1982 although there is variability. The observations of Jupiter in the present IUE program are in agreement with the recent results reported by Ref. 5, in respect to both the H Lyα bulge phenomenon and temporal trend on the time scale of the 11 year solar cycle. Although this variation corresponds well to the trend in solar H Lyα flux over the same period, two facts tend to argue against a direct correlation. First, results obtained by Ref. 7 indicate that H Lyα brightness in 1974 was an order of magnitude below the value in 1979 showing a poor correspondence with the magnitude of the solar line variation. Second, the H Lyα bulge phenomenon persists with the same magnitude in mean modulation during the years 1979-1987. The H Lyα bulge is obviously unrelated to solar flux variability. The process appears to be impossible to explain in terms of response of the atmosphere to the deposition of solar radiation.

The H Lyα emission of Saturn shows a variation of a factor of 1.7 between November 1980 and August 1981, while emission from Jupiter as well as solar flux remained basically constant over the same period. Overall, the variation of Saturn H Lyα emission is a factor of 5 from November 1980 to August 1986 (Figure 2).

The difficulty in determining and differentiating the processes controlling the emission of H Lyα mainly stems from the fact that atomic hydrogen is a minor atmospheric constituent. The abundance of HI in the atmosphere is therefore subject to a number of source and sink processes, and given the extent of available information it is difficult to determine whether variation in observed H Lyα emission rate is caused by variation in the excitation rate, in the abundance of the gas or in a combination of the two effects. The problem is complicated by the fact that some reactions producing H Lyα emission are also directly related to the production of atomic hydrogen. One of the puzzling aspects of the observed atmospheric behavior on both Jupiter and Saturn is the fact that emission in the H Lyα Rydberg bands, which serve as at least one indicator of H2 dissociation rate, do not correlate well with the observed variation of H Lyα. The H Lyα transition is excited by both electrons and resonance scattering. Dissociative excitation of H Lyα is only a small component of the observed total.

A major factor contributing to the uncertainty in understanding the behavior of H Lyα lies with the processes controlling the sink for atomic hydrogen in the atmosphere. This problem has been discussed previously by Ref. 7. The removal of atomic hydrogen from the atmosphere, apart from the process of escape (Ref. 3), can only take place by transport to the homopause with subsequent recombination. It is not clear that the factors controlling rates for this process can show substantial variability.

On the whole the evidence seems to indicate that a substantial fraction of the observed emission must be electron excited.
The persistent H Lyα bulge phenomenon on Jupiter and the tendency for independent behavior between the planets are very difficult to explain without the introduction of particle energy deposition.

4. REFERENCES

1. Shemansky, D E 1985, An explanation for the H Lyα longitudinal asymmetry in the equatorial spectrum of Jupiter; An outcrop of paradoxical energy deposition in the exosphere, J Geophys Res vol 90, 2673.


5. ACKNOWLEDGMENT

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PHENOMENOLOGICAL ANALYSIS OF JOVIAN NORTH AURORAL H₂ LYMAN BAND EMISSIONS

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Abstract

Low-dispersion spectra taken with the IUE SWP from 1981-86 are examined for gross longitudinal features in Jovian north auroral emission activity, and for evidence of long-term trends in auroral characteristics. Integrated photon flux in the H₂ Lyman band region is extracted from each of the spectra, characterizing auroral emission strength at time of exposure. A plot of flux vs. Jovian central meridian longitude (System III) corroborates an enhanced emission region centered at about 180° reported by Skinner et al. (1984). Curves fit to fluxes grouped as "scans" (consecutive exposures made over a single Jovian rotation) vs. longitude characterize width, position and intensity of the enhanced region. Study includes examination of possible long-term variation in auroral peak intensity and width of the enhanced region vs. time, as well as possible correlation of the light curve integrated over longitude as a measure of total power emitted, vs. the longitudinal position of the intensity peak, more energetic aurorae appear to peak at values of central meridian longitude lower than the previously reported 180°. An analysis is made of longitudinal dependence in the ratio of photon flux in the Lyman and Werner bands, an indicator of primary particle energy.

This work is supported by NASA grant NSE 5353

1. Unsharp-masking Background Subtraction

Background subtraction from auroral spectra was previously performed by matching a spectrum taken during minimal auroral activity to the non-H₂ emission regions of an auroral spectrum in order to remove grating-scattered light and Rayleigh-scattered solar continuum. This method permits examination of the longitudinally-independent component of the aurora but suffers from 3 defects:

1) long-time stability of longitudinally-independent component is not guaranteed
2) only a limited set of candidate background spectra is available
3) examination of non-periodic components is automatically ruled out.

Unsharp-masking eliminates high spatial frequency components (emission features) from the data spectrum via median filtration, resulting in a "background" which can be subtracted from the initial spectrum. The result is uncertain by a wavelength-independent amount, the uncertainty repaired by requiring the emission minimum at about 1300Å to be at zero, based on empirical examination of Jovian and H₂ spectra. General applicability of this method is limited by the requirement of a region of known zero emission; the non-periodic component of the auroral emission is not subtracted out and so is available for study.

2. Enhanced Emission Region

Extensive modelling by Skinner (Ref 1, 2) demonstrated that observing geometry alone (Figure 1) is insufficient to account for the apparent variation of the observed Jovian auroral flux, requiring that there be a region of enhanced emission in the auroral zone. The enhanced region is centered at ~ 180° System III longitude and extends ~ 120° around the auroral oval.

The aim of the present analysis is to describe the characteristics of the apparent variation of flux with Jovian central meridian longitude, keeping in mind the existence of a limited region of enhanced emission. Variation of those characteristics with time is then examined, taking advantage of the increased size of the data set compared to that available to Skinner (Ref 1, 2).

3. Description of Data Set and Fitting

We examine integrated photon flux in the Lyman band of H₂; the lower wavelength cutoff is selected to avoid the effects of CH₄ absorption and for consistency with Yung (Ref 3) and Skinner (Ref 2). Fluxes are drawn from 15 minute low-dispersion SWP exposures normalized by R² to the average Earth-Jupiter distance of the observations. A scatter diagram of flux vs. longitude for all auroral spectra in our data base (Figure 2) reveals wide variation about a mean configuration over the seven years of observation. The 84 asterisked points indicate members of discrete auroral "scans". Scans consist of at least 4 points, no two longitudinally-consecutive points separated by more than ~ 2.5 hours in time of observation, and at least one point on either side of a recognizable peak in flux so as to unambiguously identify the peak of the emission. This distribution is fit with a gaussian plus a constant because:

1) a gaussian has well-defined properties and fits the shape of individual scans reasonably well
2) the constant acknowledges presence of a low-level auroral emission; the constant is fixed in subsequent fits to reduce the param-

0 degrees 90 degrees 180 degrees 270 degrees

Figure 1: observing geometry for north auroral oval. The darkened segment corresponds to the region of enhanced emission.

ever space and to overcome selection effects in that the aurora has been observed mainly near peak emission.

3) the fit approximately identifies the mean auroral configuration. A similar fit is then made to individual scans to characterize the time-dependent nature of the aurora. The character of the low-level emission cannot be examined without detailed modelling of the enhanced emission region and observing geometry.

4. Variation of Fit Parameters with Time

The longitudinal position and width of the fitted emission peaks appear to be randomly distributed with respect to time; likewise the peak amplitude and rotation-averaged flux in the peak are independent of the constant (Figures 3-6). The rotation-averaged flux in the peak is a measure of the total power emitted by the longitudinally-dependent component of the aurora. There appears to be some correlation between rotation-averaged flux and the longitudinal position of the emission peak (Figure 7). The point at 209° System III longitude may be anomalous; the scan corresponding to that point is unusually bright, peaks at a considerably higher longitude than any of the other scans, and peaks at an unusually high color ratio (see below). It is conceivable that this scan may represent a different auroral process from the others.

5. Atmospheric Transmittance

The transmittance curves A, B, and C (Ref 3) (Figure 8) correspond to increasing depth of auroral emission within a model Jovian atmosphere.
atmosphere. Atmospheric absorption diminishes the Werner band relative to the Lyman band; thus the ratio of the Lyman to Werner photon flux increases for greater atmospheric depth. As the depth of energy deposition depends directly upon the energy of precipitating primary particles, the ratio can, in principle, be used with a model atmosphere and cross-section data to infer the energy of possible classes of primary particles. The ratio of the Lyman to Werner band (the inverse of Yung's (Ref 3) ratio R2) also depends upon the latitude of emission, due to the greater slant height for the emission at high latitudes than at low ones. Given the Jovian auroral geometry, there should be a peak in the ratio at 0°, when the visible portion of the auroral zone is just at the Northern limb of the planet, and a minimum at 180°, when the visible region is at ~ 60° latitude. The observed longitudinal dependence in fact varies in the opposite sense.

6. Color Ratio Versus Longitude

The color ratios are observed to peak at slightly higher longitude than the H2 Lyman intensity peak (Figure 9). Only those points included in scans are plotted here. A gaussian plus constant is fit to the scatter diagram only to approximately identify the peak in ratios and to roughly characterize the magnitude of the difference in the ratios at minimum and maximum; it is clear by inspection that the distribution is actually somewhat skewed relative to a simple gaussian.

Figure 7: Color Ratio Versus Longitude

Figure 8: Atmospheric Transmission Function

Figure 8: Atmospheric transmission for a model atmosphere as a function of wavelength, referred to emergent specific intensity for a hypothetical optically thin atmosphere (Figure from Ref. 3).

Figure 9: Scatter plot of the Lyman-band to Werner band color ratio vs. central meridian longitude. Only points drawn from scans are plotted here. The values ratioed are the average photon flux in each of the indicated wavelength regions.
Plots of color ratio for individual scans suffer more from scatter than do plots of Lyman band intensity, due to weakness of the Werner band in the relatively greater effect of random fluctuations in the apparent spectral signal. The longitude dependence could be the product of improper estimation of the unsharp-masked background within individual spectra; however, an auroral scan with the properties of the curve fit to the scattergram, would require that the flux across each spectrum in the exposures corresponding to minimum and maximum have been overestimated by 0.81 to 1.00 times the average photon flux in the Werner band of the minimum spectrum in order to wash out the longitude dependence. This is more than the difference between the background produced by unsharpmasking and the background selected by matching spectra, indicating the observed dependence is not merely an artifact of the present mode of analysis, corroborated by Skinner's similar results using the latter background-subtraction method (Ref 2).

7. Conclusions

There is no apparent long-term variation in the observed characteristics of the Jovian auroral emission. A correlation is possible between the longitude-dependent component of the emitted auroral power and the longitude at which the aurora peaks, however, an accurate statement in this regard must await a detailed modelling of the enhanced emission region in the auroral oval for each scan. Similarly, the non-longitude-dependent component of the auroral emission must await modelling for more accurate description. The behavior of the color ratios is of note as the geometrical considerations affecting the Lyman band intensities are eliminated. The peak in color ratio appears to indicate a more intense precipitation of energetic particles centered at ~ 20° System III longitude than at other longitudes. The elimination of geometry in the color ratio may also indicate that the enhanced emission region is centered at ~ 20° rather than ~ 180°; the shape of the color ratio distribution suggests that a more detailed model than that of Skinner, et al (Ref 1-2) may be necessary to model the intensity distribution in the auroral oval.

References


T A LIVENGOD, HW MOOS & GE BALLESTER
Supernovae & their Remnants
CONTRIBUTED PAPER

OBSERVATIONS OF SN 1987A: THE NARROW EMISSION LINES

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ABSTRACT

The observations of narrow emission lines of HeII, CIII, NIII, NIV, NV and OII1 in the short wavelength spectrum of SN 1987A are presented and discussed. It is shown that they originate from a circumstellar shell, which is at least a light year in size and whose nitrogen abundance relative to both carbon and oxygen is greatly enhanced as compared with cosmic values. Because of its characteristics, this shell is likely to be the remnant of the wind ejected by the progenitor star when it was a red supergiant.

Keywords: SN 1987A, Emission Lines, Nitrogen Overabundance, Circumstellar Shell, Red Supergiant

1. INTRODUCTION

There is no doubt that the observations of SN 1987A represent a big success of IUE, both technically and scientifically, and constitute possibly the most important set of observations ever made with this satellite. A close collaboration of the observing teams on both sides of the Atlantic, as well as a generous allocation of time by both NASA and ESA-SEI sides, made it possible to obtain a complete coverage of the event, starting as soon as few hours after the announced discovery and continuing unsparingly since then to catch all possible aspects of the UV spectrum evolution. A number of results have already been presented in scientific journals (Refs. 1-9) and more are either in press (Refs. 10-11) or in preparation. Some of these results are going to be presented and discussed at this Conference: Kirshner will discuss about the overall evolution of the UV spectrum of SN 1987A, Sonneborn will talk about the identification of Sk -69 202 as the SN progenitor and I will devote my talk to the discussion of the narrow emission lines which are observed in the SW spectrum since late May 1987.

2. THE UV EMISSION LINES

The story begins with the supernova short wavelength spectrum decaying steeply with time, almost a factor of ten per day for the first few days after explosion (e.g. Ref. 3). Such a precipitous drop of the SW spectrum was stopped by the presence of the two neighbor stars, creatively named star 2 and star 3, which already ten days after explosion contributed more than 80% to the observed flux shortward of 1700 Å (Refs. 3,12). By mid March the SWP spectrum was entirely dominated by the stellar contamination and, therefore, the observed flux was not varying appreciably anymore.

However, at the end of May something new happened: the continuum started rising again, but only longward of about 1850 Å and, more importantly, the presence of narrow emission lines, i.e. NV 1240 Å, NIV 1483 Å, HeII 1640 Å, OII1 1653 Å, NIII 1750 Å, CIII 1909 Å (cf. Fig. 1) was noticed (Ref. 13). They were unresolved in the low resolution spectra taken with the SWP camera, thus implying widths narrower than 1500 km s\(^{-1}\). Also, they were initially rather weak but they increased steadily with time (Fig. 2) following an essentially linear behavior (see e.g. Fig. 3). The narrow emission lines indicate that they originate in a medium with small velocity dispersion and a suitably low electron density (say, less than few 10\(^4\) cm\(^{-3}\)) so as to make the recombination times longer than about a year. A relatively low value of the density is confirmed by the peak wavelength of the 1483 Å blend of NIV (Ref. 14).

More detailed information was obtained at later times when the increased intensities made it feasible to observe the short wavelength spectrum with high resolution. A first exposure was obtained on November 25 and the lines were found to be still unresolved, thus implying a velocity dispersion in the emitting region of less than 30 km s\(^{-1}\) (Ref. 15). The emission line peaks appeared to be displaced by +284 ± 6 km s\(^{-1}\) relative to the laboratory rest wavelengths. That radial velocity virtually coincides with the strongest LMC component observed in the interstellar line spectrum of SN 1987A both in the ultraviolet (Refs. 3,11) and in the optical (Ref. 16). Therefore, not only there is a small velocity dispersion in the emitting gas but also that the systemic velocity of the emitting region relative to the SN is rather low, say, less than 10-20 km s\(^{-1}\). Moreover, an explicit estimate of the electron density can be obtained from the intensity ratio of the CIII lines 1906.68 Å and 1908.73 Å which indicates a value of \(n_e = 2-3 \times 10^4\) cm\(^{-3}\).
Figure 1. The SW spectrum from mid-March to late July, 1987. The first spectrum (labelled March) is an average "background" spectrum from March 14-28. The spectra are reddening corrected adopting E(B-V) = 0.20. Each spectrum is displaced by 5 \(10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\).

Figure 2. The averages of the difference spectra (i.e. subtracted of the mean March spectrum) are presented for a number of epochs. Note the steady increase of the NIII 1750 Å and NV 1240 Å lines.

Figure 3. The time evolution of the nitrogen lines. The intensities are in \(10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) and the time is measured in days since the explosion.
Two subsequent high dispersion observations were made, on February 25 and April 7, 1988; they not only confirm the previous results but also indicate that some evolution may have taken place in the meanwhile, in that the emission peaks seem to be red-shifted by several \( \text{km s}^{-1} \) relative to the November 25, 1987, spectrum. As an illustration, figure 4 displays the spectral region around the \( \text{CIII] \, 1906.68-1908.73 \, \AA} \) doublet for the two epochs of November 25, 1987, and February 25, 1988.

Meanwhile, narrow emission lines of \( \text{III}, \text{HeII} \) and \( \text{[OIII]} \) were also detected in the optical (Ref. 17) which confirmed the UV results and added a definite value for the line width on late November of \( \text{IPFW} = 18 \, \text{km s}^{-1} \) and direct evidence from the \( \text{[OIII]} \,(4363)/\text{II}\,(4959+5007) \) ratio for electron temperatures in excess of 30000 K.

The detailed analysis of the IUE data done by Fransson et al (1988) leads to the following conclusions:

1. Nitrogen is highly overabundant relative to both carbon and oxygen: in particular, \( \text{N/C} = 8.8 \pm 3.3 \) and \( \text{N/O} = 1.5 \pm 0.8 \), which are 32 and 11 times higher than the corresponding solar ratios.

2. The electron density is about \( 2.5 \times 10^4 \, \text{cm}^{-3} \) and the electron temperature about or slightly higher than 30000 K.

3. The total size of the emitting region is at least one light year; this follows from the consideration that the line intensities are still increasing a year after the explosion, while the ionization is likely to have occurred at the initial UV burst of the SN explosion. The apparent evolution of the emission line intensities is due to light travel effects for which we see larger and larger fractions of the emitting region as time proceeds. Eventually the intensity rise will level off when radiation from the whole region will be received.

4. The emitting mass as of November 1987 is at least 0.05 \( M_\odot \) (but probably not much higher than twice that value). Combining this result with the estimates of the density and the diameter, the width of the emitting region turns out to be very small, definitely much smaller than its radius.

5. The expansion velocity of the emitting gas is less than 100 \( \text{km s}^{-1} \) and, possibly as low as 10 \( \text{km s}^{-1} \); this follows from the narrow, unresolved profiles of the UV lines and the observations of the optical line profile as reported by Ref. 17.

This observational picture of the emitting region is suggestive of a circumstellar shell of CNO processed material, such as expected in the wind of a moderately massive red supergiant. In fact both the abundances and the implied
mass loss rate (i.e. roughly $\dot{M} \sim (\text{shell mass})/(\text{shell radius})/(\text{expansion velocity}) \sim 1.5 \times 10^{-6} \text{ M}_\odot \text{ yr}^{-1}$) are perfectly consistent with that hypothesis. The red supergiant wind, however, must have been compressed quite a bit in order to reach the observed density; this is the effect of the pressure exercised by the much faster stellar wind ejected by the SN progenitor in the subsequent phase when it had become a blue supergiant.

Although one can anticipate that refinements in both the overall picture and the physical parameters will be obtained when the observations will extend so as to cover the leveling-off phase of the line intensities, the basic interpretation should not change appreciably.

On the other hand, there is still a lot of excitement to expect with this supernova. In particular, the interaction of the SN ejecta, which are moving at speeds as high as 30000 km s$^{-1}$ in the outermost layers, with the UV line emitting shell will produce another phase of intense emission, possibly both in the UV and in the X-ray domains. Thus, we can expect fireworks to start cracking in about ten years from now: just be patient...

REFERENCES

CONTRIBUTED PAPER
THE PROGENITOR OF SN 1987A

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ABSTRACT

Spatially resolved IUE spectra (1150 - 2000 Å) taken at the position of SN 1987A in Mardia 1PS7 show that the 12th mag B3 star Sk-69° 202 has disappeared. Only the two fainter companion stars (Star 2 and Star 3) are now present near the site of the supernova. Sk-69° 202 is the star which exploded to produce SN 1987A. The known characteristics of Sk-69° 202 are consistent with the interpretation that the progenitor was a relatively compact star, having a high-velocity low-density stellar wind prior to the outburst. Recent IUE spectra of SN 1987A (May 1988) show no evidence that Sk-69° 202 still exists inside the expanding ejecta.

Keywords: Supernovae, ultraviolet spectra

I. INTRODUCTION

It came as a surprise to those following the early observations of SN 1987A that the definitive identification of the progenitor would be made in the ultraviolet. However, the discovery that the supernova's far ultraviolet flux faded by three orders of magnitude in the first four days of the outburst (Ref. 1), revealing a constant, stellar background flux, presented us with an unexpected opportunity to examine the supernova's immediate surroundings for the survivors. By 27 February 1987 the far UV flux had dropped to a level where a constant, stellar background was detected shortward of 1500 Å.

Analysis of preoutburst plates revealed an excellent positional coincidence between the supernova and the 12th mag B3 I star Sk-69° 202 (Ref. 2) and the presence of a second star 3 arc sec to the NW (Ref. 3). Similarities between the IUE spectrum of the UV source at the position of the supernova and that of a luminous early-type star seemed to imply (Ref. 1) that Sk-69° 202 might have survived the explosion.

It was soon discovered that IUE spectra of SN 1987A were broadened perpendicular to the dispersion shortward of 1500 Å, indicating the presence of more than one source in the 10° x 20° aperture during the supernova exposures (Ref. 5). The detection of two early-type UV stellar spectra at the site of the fading supernova and the identification of two blue stars in the Sk-69° 202 system seemed to imply that the spectra came from the two stars: Sk-69° 202 (Star 1) and Star 2.

Subsequently, high-precision measurements and image syntheses of the Sk-69° 202 field (Ref. 6) demonstrated the reality of a third star and provided accurate relative positions for the three members of the Sk-69° 202 system. Star 3 was about two magnitudes brighter than previously thought (m_o = 15.5), about 1.6 arc sec SE of Star 1, and also blue in color. This review summarizes the work (Refs. 7 and 8) which demonstrates that the objects detected near the supernova in IUE spectra are Stars 2 and 3 and that Sk-69° 202 is no longer present.

II. OBSERVATIONS AND DATA ANALYSIS

The identity and characteristics of the stars within several arc seconds of the supernova, and detected in IUE spectra, are determined by analysis of SWP low-dispersion spectra taken after 1 March 1987. During this period the far UV flux of the supernova was much weaker than the other sources in the aperture and the projected separation of Stars 2 and 3 was sufficiently large to allow deconvolution of their spectra. The analysis described below makes use of IUE spatially-resolved low-dispersion spectra, the so-called Extended Line-By-Line (ELBL) spectra (see Refs. 9 and 10).

The relative positions of Stars 1, 2, and 3 from Ref. 6 were adopted for comparison with the IUE data. The orientation of the three stars and the large aperture are shown to scale in Figure 1. The aperture orientation on the sky is determined by the satellite's solar array orientation. Because the Large Magellanic Cloud is located near the south ecliptic pole, IUE's array orientation changes about one degree per day. It was completely fortuitous that the stars within a few arc seconds of SN 1987A were in near-optimal alignment with the spectrograph's spatial direction at the time when the supernova's UV flux faded.
Figure 1. Changing IUE aperture orientation with respect to the SN 1987A field. The astrometric positions (Ref. 6) of Stars 2 and 3 are shown relative to Star 1. The outline of the aperture is shown for three dates 27 February, 13 and 22 March 1987. The straight line is the direction perpendicular to the dispersion for the 13 March date (solid line). (From Ref. 8)

The 1250 – 1600 Å ELBL data from 13 March (SWP 30512) are compared in Figure 2 with similar data for a single point source. The spectral data have been averaged in 50 Å intervals; no binning or smoothing has been applied in the spatial direction. The presence of two sources in the aperture during the supernova exposure is apparent. The FWHM of the IUE point-spread function (PSF) in SWP spectra varies between 4.6 arc sec at 1350 Å to 6.0 arc sec at 1900 Å (Ref. 11). A good photographic representation of the spatially-resolved spectra of Stars 2 and 3 is shown in Ref. 7.

Numerical procedures were developed to analyze overlapping spectra in IUE low-dispersion images (Ref. 12). Multiple PSFs are fit to the spatial profile of the ELBL data with a multi-variable least squares fitting technique, adopting the skewed-gaussian form of the IUE PSF (Ref. 11). Figure 3 compares the variation in the mean separation between two PSFs with that expected for Stars 1 and 2 and for Stars 2 and 3. A more detailed discussion of the fitting procedure is given in Ref. 8. The variation depicted in Figure 3 is the result of changing IUE aperture orientation due to solar array constraints.

![Figure 2](image1.png)

Figure 2. Low-dispersion SWP spatially-resolved spectra. a) The ELBL data for a single point source is shown at 50 Å intervals from 1275 to 1575 Å. b) The ELBL data for one of the supernova images (SWP 30512, 13 March) shows the presence of two sources close to the position of SN 1987A. (From Ref. 8)

![Figure 3](image2.png)

Figure 3. The measured (diamonds) and predicted (solid dots and line) separation between Stars 2 and 3 as a function of time. The expected separation between Stars 1 and 2 is also shown (large dashed line). The small dashed line represents a 4° change in the Star 2-3 position angle to 133.°7. (From Ref. 8)

III. RESULTS

The measured separations between the two spectra are in very good agreement with the astrometry of Walborn et al. (Ref. 6) only if the observed stars are Stars 2 and 3. The results are not consistent with the expected separation between Stars 1 and 2. The error in the component separations, which includes the estimated uncertainty in the IUE spatial scale and the rms error in the least-squares fits to each 25 Å section of the spatial profile, are small, generally less than 5% of the gaussian FWHM. We do not know the relative contributions to the small systematic differences between measured and predicted separations from measurement error in the astrometric positions and in the IUE analysis and spatial scale. However, these differences can be accounted for by a 4° rotation of the Star 2 – Star 3 position angle, as shown in Figure 3.

Two point sources produce an excellent fit to the ELBL data ($\lambda < 1500$) taken after about 1 March, with flux residuals (data – computed fit) of several percent of the height.
of the gaussian PSF (Fig. 4a). However, there was a period of a day or two at the end of February when Stars 2 and 3 and SN 1987A had comparable UV flux levels below 1500 Å. A two component fit to these data yields large flux residuals of 25–30% (Fig. 4b). When three point sources are fit to the same data an excellent result is obtained, with flux residuals again close to several percent (Fig. 4c). The third point source is located between Stars 2 and 3, 2.9±0.3 arc sec from Star 2, in good agreement with the position of Sk -69° 202 / SN 1987A with respect to Stars 2 and 3.

The gaussian fitting procedure also determines the relative contribution of Stars 2 and 3 to the total flux for the entire SWP wavelength range. The deconvolved spectra of stars 2 and 3 are shown in Figure 5. They have the appearance of early-B spectral types. The strength of the numerous interstellar lines in both spectra is consistent with IUE low-dispersion spectra of other LMC early-type stars. Both Stars 2 and 3 must be located in the LMC, and are not foreground objects.

Dereddened fluxes for Stars 2 and 3 have been determined by comparing their deconvolved spectra with the Kurucz (Ref. 13 and unpublished) model atmosphere grid. The reddening was estimated from the colors of Sk -69° 202 (Ref. 14) and recent work on intrinsic colors of LMC supergiants (Ref. 15). A two component extinction has been adopted: $E(B-V)_{Gal} = 0.08$ from the Galaxy (Ref. 16) and $E(B-V)_{LMC} = 0.10$ from the LMC (30 Doradus curve from Ref. 17), for a total $E(B-V)$ of 0.18. The one-third solar abundance Kurucz models which give the best fit to the continuum slopes are: $T_{eff} = 20000K$ and 25000K (± 2000K) and $\log g = 3.0$ and 4.5 (± 0.5) for Stars 2 and 3, respectively. This suggests that Star 2 might be slightly evolved (luminosity class IV or III). However, the deconvolved spectra are noisy and not of high enough quality to reliably assign spectral types and luminosity classes.

In summary, only two of the original three stars comprising the Sk -69° 202 system are detected in spatially-resolved UV spectra taken at the position of SN 1987A. The temporal variation of the spectral separation is in good agreement with that expected for the positions of Stars 2 and 3 measured on preoutburst plates. Furthermore, in late February 1987 the location of the supernova spectrum shortward of 1500 Å , relative to Stars 2 and 3, was in excellent agreement with the expected position of Star 1. Sk -69° 202 is absent from the field and was therefore the progenitor of SN 1987A. The known characteristics of Sk -69° 202 are consistent with the interpretation that the progenitor was a relatively compact star (Ref. 18), having a high-velocity low-density stellar wind prior to the outburst (Ref. 19). Recent IUE spectra of SN 1987A (May 1988) show no evidence that Sk -69° 202 still exists inside the expanding ejecta.
References

The Complete Visual Light Curve of SN 1987A:
Thirteen Months of FES Observations

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ABSTRACT

Visual brightness measurements of SN 1987A are being obtained with the IUE acquisition camera and star tracker (Fine Error Sensor, or FES) as part of each ultraviolet observation. Due to IUE's around-the-clock operation and lack of clouds, the FES record of SN 1987A is perhaps the most complete set of visual photometry of the supernova made by any single instrument. These data illustrate the photometric limitations of the FES (± 0.03 mag). Use of differential photometric methods are recommended for IUE observers desiring accurate photometry from FES measurements made during their observing shifts.

Keywords: Supernovae, visual light curves, differential photometry

1. INTRODUCTION

The IUE Fine Error Sensor plays an integral role in the target acquisition for each spectral observation made by the satellite's spectrograph/camera systems (Refs. 1 and 2). Prior to each exposure of the supernova, as for virtually all exposures of objects 14 mag < V < -1 mag, the target's center of light is positioned at a standard position (the "Reference Point") in the telescope field of view. From the Reference Point canned slews are used to accurately position the target in the spectrograph aperture. The process of positioning the supernova's center of light produces a mean brightness measurement. These FES counts have been recorded for each observation of SN 1987A at GSFC.
to produce a database with over 520 entries as of 18 April 1988. The complete IUE light curve for SN 1987A is shown in Figure 1, which includes all corrections discussed below.

The FES is an image disector with an unfiltered S20 photocathode, and therefore has a very broad spectral response (~ 4000-7000 Å). Despite its moderate photometric precision it has proved to be very useful because it is available 24 hours per day and is not vulnerable to bad weather or seeing conditions.

2. OBSERVATIONS

The first FES measurements of SN 1987A were made on 24.812 February 1987, about 1.5 days after the outburst began. The time of outburst is taken to coincide with the Kamiokande-II and IMB neutrino detections (23.316 February 1987, Refs. 3, 4). SN 1987A was observed daily by IUE from 24 February through late May 1987, approximately every other day during June, July, and August, and with decreasing frequency since then. Observations are now obtained every 7-10 days. During each observing period FES counts for SN 1987A were measured with the supernova accurately positioned at the Reference Point as part of the normal process of obtaining UV spectra.

The FES was used in the Underlap Mode (used for $m_p < 4.8$) for all observations of SN 1987A prior to mid-July. Measurements were made in both Underlap and Overlap modes through March 1988, and only in Overlap thereafter. Collection of FES data in both scan modes was continued as long as possible so as to build up a unique data base of FES measurements which will improve the FES photometric calibration. All data to date have been in the Fast Track scan rate.

The FES calibration of Imhoff (Ref. 5) was used to derive FES V magnitudes, which includes a correction for time-dependent changes in the FES sensitivity. No correction has been made for the small (B-V) dependence in the calibration. A significant part of the loss of sensitivity appears to be due to a "fatigue spot" on the FES aperture plate located precisely at the Reference Point. The origin of this fatigue spot is unknown, but might plausibly arise from long-term damage to the Reference Point's location of the photocathode due to 10 years of accumulated target acquisition activity. This effect accounts for the majority of the sensitivity change (Ref. 6).

The Underlap data for SN 1987A was found to have low scatter (± 0.03 mag). However, the Overlap data obtained at the same time had much larger scatter, even though every precaution was taken to ensure that the target was properly centered at the Reference Point. Beginning in early October 1987 a star of similar brightness and color close to the supernova was observed with the FES within an hour of the SN 1987A measurements so that differential methods could be used. The comparison star was HD 45669 (K5 III, V=5.56, (B-V)=1.51). A moderately red star was chosen as an approximation to the general spectral distribution of SN 1987A, even though there are significant differences between a K star and the supernova's spectrum (most notably the strong emission lines).

Figure 2 shows the variation in FES counts for HD 45669 from October 1987 to April 1988. Two points should be noted: First, there is a long-term decline in mean brightness of about 7.8%. During this time period, the supernova's FES counts decreased from about 18000 to 4000. Second, there is a large short-term variability. The latter appears to be instrumental because the FES counts of SN 1987A vary in exactly the same manner. Figure 3 shows the uncorrected FES magnitudes for SN 1987A. In Figure 4 is shown the same data when the FES counts for SN 1987A are increased or decreased for the day to day fluctuations about the mean for HD 45669 (the solid line in Figure 3). This procedure results in a significant improvement in the scatter, comparable to that in Underlap mode. The corrected magnitudes shown in Figure 4 are an expanded version of the data in Figure 1.

The long-term decline in counts for HD 45669 is believed to be due to the FES fatigue spot. The origin of the day to day variations is unknown, but instrumental effects are suspected. The short-term changes actually occur on a time scale of hours (Ref. 7).
3. DISCUSSION

The SN 1987A light curve has been widely discussed (e.g. Refs. 8-10). The IUE FES data agrees well with ground-based measurements. The data clearly shows the exponential decay portion between days 140-210. After that, however, there is a gradual deviation from a linear (in magnitudes) decay rate as the supernova becomes fainter at a slightly faster rate. This first became evident in the IUE data in early January 1988 (Ref. 11). Looking back at the data, the non-exponential decrease was underway by late November (~ day 250), corresponding closely to the emergence of gamma rays from the supernova ejecta (Refs. 12-15).

The deviation from an exponential decline is now quite large (over 0.5 mag). Figure 5 shows the deviation from the exponential decay light curve predicted from days 140-210. If the FES bandpass closely approximates the bolometric light curve, then this implies that over 30% of the gamma-ray energy is escaping, either as gamma rays or at slightly lower energies in the X-ray spectrum, and is not contributing to the visual spectrum.

References

SPECTRAL EVOLUTION OF SN 1987A
IN THE IUE LONG WAVELENGTH RANGE


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Abstract

IUE low resolution spectra of SN 1987A, in the long wavelength range, (1952 - 3348Å), obtained in the period Feb 25, 1987 - Mar 17, 1988, have been analyzed to study its spectral evolution. We study the spectral variations by comparing spectra obtained at two consecutive observing dates.

1 Velocities

The IUE low resolution monitoring of SN 1987A shows a general decrease of the expansion velocities with time. This is demonstrated by the progressive narrowing of the absorption features and by their progressive shift toward the red. In order to gain insight on the spectroscopic evolution of the SN, it is necessary to take the effects of the expansion velocity into account. To this purpose we have used the spectrum of Jan 13, 1988 as reference, and applied relative velocity corrections to the earlier spectra. After the velocity correction, one can more easily identify the spectral features and detect the major spectroscopic changes, as shown in Fig. 1. In Fig. 2 we show the velocities derived from the major UV multiplets. The velocities derived in this way are consistent with those found for the higher Balmer lines by others in the optical, (e.g., Phillips et al., 1987).

2 Spectral Evolution

The spectral evolution of SN 1987A in the early stages has been described by Cassatella et al.,1987; Cassatella, 1987; Lucy, 1987; and Spies et al., 1988. Here we provide preliminary information for the later stages. The spectral features in SN 1987A on Feb 26 and at later dates can be explained mainly by blends of FeII and TiII lines.

References

Figure 1: Spectroscopic evolution of SN 1987A in the IUE-LWP range. Individual spectra have been corrected for velocity shifts using the spectrum of Jan 13, 1988 as reference. The dates of observation are as follows:

a) January 13, 1988
b) top: February 26; (flux divided by 2); bottom: February 27, 1987
c) from top to bottom: March 1, 2, 4, 1987
d) top: April 28; bottom: April 5, 1987
e) top: May 14; bottom: June 8, 1987
f) top: September 20; bottom: July 16, 1987.

Figure 2: Velocity shifts from the major UV multiplets dominating the spectral appearance of the SN in the long wavelength range.

Figure 3: Light curves of the SN 1987A around Till V4, (3100 - $\lambda$ - 3150 $\AA$), and Fell UV32-63, (2620 - $\lambda$ - 2780 $\AA$), after velocity correction.
IUE OBSERVATIONS OF OXYGEN-RICH SUPERNOVA REMNANTS

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Oxygen-rich supernova remnants present an opportunity to observe material ejected in type II supernova explosions. IUE observations help to determine the composition of the ejecta (especially C and Si abundances) and to test models for the ionization and excitation of the ejecta. We present UV observations of two oxygen-rich supernova remnants (N132D in The Large Magellanic Cloud and IE 0102-7219 in the Small Magellanic Cloud) and discuss the similarities and differences between them.

Keywords: nebulæ supernova remnants - nucleosynthesis - abundances

1. Introduction

A few supernova remnants (SNRs) contain remarkable high velocity knots of material entirely devoid of hydrogen and helium. At optical wavelengths these knots emit [O II] and [O III] lines most strongly, with weaker lines of neon, sulfur, calcium and argon in some cases (Refs. 6 and 13) and sometimes neutral oxygen recombination lines (Ref. 18).

The elemental composition of this high velocity material, undiluted since its ejection by the supernova explosion, provides a look at the products of nucleosynthesis inside the progenitor star before and during the explosion. It therefore provides a direct test of stellar evolution and nucleosynthesis calculations. Ultraviolet observations are extremely important for such tests, because all the strong emission lines of carbon, magnesium and silicon are located in the IUE wavelength range. In addition, ultraviolet observations can provide tests of models for the excitation and ionization of the ejected material by shock waves (Refs. 6 and 11) or by photoionization (Ref. 3).

Of the seven remnants known to possess hydrogen-free knots, three are in our galaxy (Puppis A, Cas A and G292.0+1.8) and are unfortunately too highly reddened for IUE study. The SNR in NGC 4149 is extremely luminous intrinsically, but is so distant that only a weak detection of [O III]λ1063 was possible with IUE (Ref. 2). The Large Magellanic Cloud remnant 0510-603 is not only oxygen-rich, but also shows many similarities to the Crab Nebula; IUE observations of this object have been attempted twice, but only a faint continuum from the object has been detected (see Ref. 1). Only the supernova remnants N132D in The Large Magellanic Cloud and IE 0102-7219 in The Small Magellanic Cloud are sufficiently bright and unreddened for detailed study with IUE. Below we discuss our IUE observations of these two objects and the conclusions that can be drawn from combined UV/optical data.

2. IUE Observations

Both N132D and IE 0102-7219 show optical emission knots that are bright in the forbidden lines of oxygen and neon, with expansion velocities of 2250 and 6500 km s⁻¹ and diameters of 32 and 6.9 pc, respectively (Refs. 7, 14 and 17). Although the exact relative line intensities differ, by-in-large the optical spectra are quite similar. This is in contrast to what we have found in the UV.

We have combined ESA and NASA shifts to obtain SWP and LWP exposures on bright portions of O-rich material in each of these objects. The IUE spectra have been reduced from the extended line-by-line files at the RDAF at NASA/GSFC. Reseau marks, hits and hot camera pixels were removed from the line-by-line data before re-extracting the spectra. Figures 1a and 1b show the resulting SWP and LWP spectra of N132D, while Figure 2a and 2b show the corresponding spectra of IE 0102-7219. Table I presents fluxes from these observations, which
correspond to the northeastern edge of the N132D ring and the southeastern side of IE 0102-7219. The line intensities have not been corrected for reddening, but with E(B-V) = .08 - .09 (Refs. 3 and 14), the relative intensities of the UV lines are only marginally affected.

Comparison of the spectra and the line intensities shown in Table 1 indicates both similarities and differences in the emission from the two objects. Many of the same lines are seen although the relative intensities vary. No Si III] λ1862 emission is detected, so the λ1400 feature can be attributed to O IV] in both objects. Comparison of the observed line strengths indicates that the gas in IE 0102-7219 has larger C, Ne and Mg abundances relative to O than in N132D by a factor of roughly two.

One of the most striking differences between the two spectra is the O I λ1355 line, which is at least twice as strong as O III] λ1463 in IE 0102-7219, but entirely absent in N132D. This line is formed by recombination (Ref. 3), along with the optical λ7774 multiplet (Refs. 12 and 18). This identification is confirmed by optical spectra, which show the λ7774 line present in IE 0102-7219 (Ref. 3), but not in N132D (unpublished spectrum). For the SMC remnant, the relative intensities of λ1355 and λ7774 can be used to scale the UV and optical line intensities, since these lines come from the same recombination cascade.

Another difference in the spectra is the presence of strong C II]λ2325 emission in N132D while none was detected in IE 0102-7219. The presence of C II], C III] and C IV emission lines at comparable intensities in the UV spectrum of N132D (and the absence of the O I recombination lines) is a strong indicator that shock heating is responsible for exciting the emission in this object. The absence of C II] in the spectrum of the SMC remnant even though the carbon abundance is higher calls into question whether shocks are the main cause of the observed emission.

A related difference is apparent when the UV and optical line intensities are compared. In the SMC remnant, the UV lines are weaker than expected from most shock models with respect to the optical lines. The cleanest line ratio that demonstrates this is O III] λ1663/λ15007], which depends only on the temperature in the O ] region. This ratio in IE 0102-7219 is only 0.08 after reddening correction (Ref. 3). Shock wave models predict I(1663)/I(5007) in the range 0.3 - 0.9 (Refs. 6 and 12), which is difficult to avoid since the ratio is only weakly temperature dependent at electron temperatures high enough to collisionally ionize O III] to O IV]. For N132D we do not yet have an accurate UV to optical normalization, but from a crude comparison with the surface brightness estimate in Ref. 14, the ratio is between 0.15 and 0.60, roughly in accord with the expectations of shock heating.

3. Models and Interpretation

The differences mentioned above may well be related to differences in the mechanism exciting the emission in each object. The N132D observations were only made recently so we have not yet calculated detailed models for this object. Comparison of our observed UV line intensities to published models of a given shock velocity or set of assumed abundances (Refs. 6 and 12) do not provide a good match. However, the large IUE aperture no doubt samples material with a range of densities, shock velocities and compositions. The qualitative indicators discussed above provide convincing evidence that shock heating is the dominant excitation source in N132D.

Since IE 0102-7219 is the strongest extended soft X-ray source in the SMC (Ref. 16), we consider RX-ray photoionization models for this object. The 1.5 X 10^27 ergs s^-1 RX-ray luminosity of IE 0102-7219 (Ref. 9) implies an RX-ray flux to density ratio far higher than in the other known oxygen-rich SNRs, and photoionization should be correspondingly more important. Detailed measurements of the RX-ray spectrum are not available, so we have used the RX-ray emission code described in Ref. 15 with updated atomic data summarized in Ref. 5 to generate model spectra covering the 5-1000 eV energy range at 2.1 eV resolution. Models of young SNRs generally show very strong emission from the helium-like ions of the elements present (e.g. Refs. 8 and 10) so we have added the emission of carbon in a 10^6 K plasma, oxygen at 1.6 X 10^6 K, and neon at 3 X 10^6 K to give a spectrum resembling those predicted by models. Several variants on this RX-ray spectrum were used to examine the sensitivity of the results to the assumed RX-ray spectrum. In particular, we tried much stronger carbon line emission, strong EUV emission in lines such as O V λ530, and attenuated EUV emission to simulate the effects of absorption by the optically bright gas. These alternatives changed the equilibrium temperatures of the photoionized gas by ≤ 30% and some of the line ratios by factors of two, but they do not alter the general conclusions below.

The RX-ray spectrum was used to compute the equilibrium ionization state and heating rate of gas at various densities, and the temperature was iterated until radiative cooling balanced the heating. The abundances assumed were appropriate for the ejecta from a Type II SN explosion. Some typical results of these models are as follows. The gas in the SMC remnant must span a wide range in density. Regions denser than about 10 cm^-3 are needed to produce the O I recombination lines, but they are too cold to produce any line excitation except in the far infrared. Regions near 1 cm^-3 are warm enough to produce the observed ultraviolet lines, but the temperatures are low enough that the UV to optical line ratios are modest. A fraction of order 10^3 of the apparent volume...
OXYGEN-RICH SUPERNOVA REMNANTS

Figure 1: IUE spectra of Ni32D in the Large Magellanic Cloud. a) SWP 31578, 685 minute exposure. b) LWP 12671, 730 minute exposure. Hits and reseau marks have been removed and the data have been smoothed over three pixels.

Figure 2: IUE spectra of 1E 0102-7219 in the Small Magellanic Cloud. a) SWP 27926, 865 minute exposure. b) LWP 7845, 840 minute exposure. Hits and reseau marks have been removed and the data have been smoothed over three pixels.

Table 1

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<tr>
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<th>1E 0102-7219</th>
<th>Ni32D</th>
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<td>1335</td>
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<td>8</td>
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<tr>
<td>O I</td>
<td>1355</td>
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<td>13</td>
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<td>152</td>
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<tr>
<td>C IV</td>
<td>1550</td>
<td>600</td>
<td>170</td>
</tr>
<tr>
<td>Ne II</td>
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<td>Mg II</td>
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Table 1

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<td>[O III]</td>
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<td>92</td>
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<tr>
<td>Mg II</td>
<td>2700</td>
<td>74</td>
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</tbody>
</table>

Table 1

of a torus 3.5 pc in radius with a minor radius one tenth as large containing gas at a density $n_0 \approx 1 \text{ cm}^{-3}$ can account for the observed [O III] optical luminosity, and similar volumes at higher densities can produce the oxygen recombination radiation and the UV lines.

There are two major difficulties with the equilibrium photoionization models. First, the [O II]/[O III] ratio is predicted to be less than about 0.3, while the observed ratio varies between 1.3 and 2. This reflects the fact that oxygen is mostly doubly ionized in models warm enough to effectively excite the λ3727 transition. Second, the [O III] emission comes mostly from 10,000 - 15,000 K gas in the model, but the $I(3863)/I(5007)$ ratio suggests a temperature of 25,000 K.

Both difficulties may be related to an unwarranted assumption of ionization equilibrium. While the heating and cooling timescales are a few years, so that thermal balance is a valid approximation, the ionization timescales are $\sim 2000$ years, which is close
to the expansion age of 1E 0102-7219. Hence, time
dependent models should give a lower ionization state
than predicted by the equilibrium model and also be
somewhat warmer. We have run a series of time-
dependent photoionization models where gas having
the same abundances as above was allowed to expand
freely at 3600 km s\(^{-1}\) for 2400 years while exposed to
the X-ray flux described above. The gas was initially
taken to be cold and neutral, but the initial conditions
turned out to be irrelevant since the gas always cooled
quickly, then slowly warmed and ionized late in the
evolution.

Again, these models indicate that a mixture of
densities is needed to produce both the high ionization
lines and the O I recombination lines. These particular
models improve the \([\text{O II}]/[\text{O III}]\) ratio, but still fall
short of the observed value. They also predict a larger
C III/C IV ratio than observed and far too much C II\(^{\lambda 325}\)
This problem could be alleviated by increasing the
carbon line intensities and decreasing the oxygen
lines in the ionizing X-ray spectrum. However,
considering the number of free parameters, we are loath to adjust the model parameters to try to
"fit" the observed spectrum.

In summary, time-dependent photoionization by
the EUV and X-ray radiation from 1E 0102-7219 can qualitatively explain its UV and optical line emission,
but the density and ionization structures are complex
and prevent a unique model from being specified.
Many model parameters are poorly constrained,
including the time dependence and shape of the ionizing
spectrum. Moreover, the models presented here
are not self-consistent in that the volumes and densities
of the optically emitting gas imply optical depths
of order unity in the EUV, but absorption of the ionizing
radiation has been ignored.

It is possible that these shortcomings reflect a
more fundamental limitation of the model assumptions.
We have assumed throughout that the electron
velocity distribution is Maxwellian and that the energy
deposited by photoionization heats the electrons
directly. In fact, the ~500 eV electrons produced by
the Auger process may excite or ionize other ions before they slow down enough to share their energy
with other electrons. Many of the excitations would
produce photons that could ionize lower ionization
stages.

Our inability to define a unique model for either
of these objects at present may also be related to the
complexity of the objects themselves. It may be that
shocks and photoionization are needed to explain the
emission from the SMC remnant. Spatial variations in
composition or physical conditions such as are seen in

Gas A (Ref. 4) would tend to be averaged together in
our IUE large aperture spectra, which incorporate a
fair fraction of the emission from each object; this
would make a unique interpretation very difficult.
Also, differences in aperture positions and sizes
between UV and optical spectra can cause confusion if
spatial variation- are present. Higher spatial resolution
observation- and combined UV/optical coverage
with the same aperture sizes will be strengths of the
Faint Object Spectrograph on the Hubble Space Tele­
scope, and we plan to continue these studies with that
instrument when it becomes available.

It is a pleasure to thank the dedicated staff of the
IUE Observatory on both sides of the Atlantic for
their part in helping procure the ultraviolet data.
This project has been supported by the following
grants: NAG 5-701 and NAG 5-988 to The Johns
Hopkins University, and NAG 5-87 to the Smithsonian
Astrophysical Observatory.

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931.
142.
35, 410.
981.
EJECTA IN SN 100G: THE KNOTTY ISSUE

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Center for Astrophysics
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Boulder, Colorado 80309

ABSTRACT

We present new 19SS 1UE SWP observations of a faint sdOB star situated behind the remnant of the supernova of AD 1006. These spectra along with previous IUE spectra of the star taken between 19S2 and 19SG provide a detailed look at the elemental composition and dynamical properties of the SN 100G remnant. Over the six years there have been no significant changes in the absorption features associated with the remnant at 1281, 1330, or 1420 Å. While the lack of variability in these absorption lines makes it impossible to decide whether the éjecta is distributed smoothly or in knots, it is now clear that the 1281 Å feature is a blend, requiring either SI II absorption redshifted at 5000 km s\(^{-1}\) plus Si II 1255 at 5200 km s\(^{-1}\), or else two individual Si absorbing regions.

Keywords: supernovae - supernova remnants - interstellar medium - stars: sdOD

I INTRODUCTION

The galactic radio source G327.6+14.6 is the probable remnant of the bright historical supernova observed in 1006 AD. This remnant appears in the radio and X-rays as a limb brightened 30' diameter shell. Optically, there are just a few thin Balmer dominated filaments along the northwest rim. The similarity of the SN 1006 remnant's morphology and optical emission to Tycho's SNR, its high galactic latitude, the supernova's reported visual brightness and time of visibility, together with a lack of a nearby OB association have strongly suggested a Type Ia origin for SN 1006. Current models for Type Ia SN involve the disruption of a white dwarf either through mass accretion in a close binary or the merge of two white dwarfs.

Strong support for both the Type Ia nature of SN 1006 and exploding carbon-deflagration white dwarf models has come from IUE observations of a faint sdOB star positioned behind the SN 1006 remnant. Low dispersion IUE spectra of this star, referred to as the S-M star (Schweizer and Mid-dleditch 1980), reveal several strong and broad absorption features which are uncharacteristic of a sdOB star (Wu et al. 1983; Fesen et al. 1988). Specifically, there are very strong Fe II absorptions at 1610, 2370, and 2600 Å with a velocity range of ±5000 km s\(^{-1}\), plus broad features at 1281, 1330, and 1420 Å. The latter features have been interpreted by Wu et al. (1983) and Fesen et al. (1988) as 1200 Si II, 1255, 1259 S II, 1302 O I, and 1393, 1403 Si IV redshifted by 5000 - 6500 km s\(^{-1}\). The presence of an expanding sphere of iron-rich éjecta interior to O, S, and Si-rich material having velocities in excess of that seen for the iron is consistent both with observations of Type Ia SNe near maximum light, and with carbon deflagration models.

If the Si, S, and O features are caused by fast-moving knots of éjecta with dimensions on the order of 10\(^{-1}\) pc, such as is observed in other young remnants, then noticeable changes in their absorption profiles and strengths can be expected on a time scale of about 10 years. In order to investigate possible changes in these absorption features, we obtained new 1988 SWP spectra of the S-M star. Below, we describe the observations and results and discuss the issue of knots of éjecta in SN 1006.

II OBSERVATIONS

Low-dispersion, short wavelength (SWP) IUE spectra of the S-M star were obtained on March 25 and 26, 1988. The exposure times were 400 minutes (SWP 3315G) and 415 minutes (SWP 33164) respectively and were taken during very low radiation levels in US1 observing shifts. A log of all IUE SWP of the S-M star is given in Table 1. The two new low dispersion spectra were extracted from the spatially resolved line-by-line file provided by IUESIPS using either 5 or 7 lines. Standard calibrations and blemish corrections were applied. Placement of the S-M star within

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<tr>
<td>SWP 19927</td>
<td>8 May 1983</td>
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<td>SWP 27592</td>
<td>25 Jan 1986</td>
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<td>27 Jan 1986</td>
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</tr>
<tr>
<td>SWP 33156</td>
<td>25 Mar 1988</td>
<td>400 min</td>
</tr>
<tr>
<td>SWP 33164</td>
<td>26 Mar 1988</td>
<td>415 min</td>
</tr>
</tbody>
</table>

the large aperture was done via a blind offset slew. Slight relative displacements of the star within the large aperture can result in small wavelength shifts, a not uncommon problem. Offset displacements of the S-M star of the order of 2 - 4" apparently occurred for these new observations since stellar absorption features at 1550 (C IV) and 1640 (He II) in these 1988 spectra showed wavelength differences of 7 and 6 Å with respect to rest wavelengths. The spectra were consequently shifted by these amounts so they could be compared and added to previous IUE spectra.

The two new spectra smoothed by a 3 point box-car function and then added together are shown in Figure 1 along with 1982/1983 and 1986 summed spectra. The summed spectrum from the three epochs is shown in Figure 2 with the major absorption features identified.

![Figure 1](image1.png)

**Figure 1** — Plot of summed 1982/83, 1986, and 1988 SWP spectra of the S-M star for the wavelength range 1200 to 1700 Å. Summed data as shown have been smoothed by a three point box-car function and wavelength corrected relative to the 1982 spectrum (SWP 16054).

![Figure 2](image2.png)

**Figure 2** — Sum of all six low-dispersion SWP spectra of the S-M star for the wavelength region 1200 to 1700 Å. Probable line identifications for the stronger features are indicated.

III DISCUSSION: KNOTS OR NOT?

From the six IUE spectra taken over a period of six years, we can now better determine the reality and variability of absorption features in the S-M star. The absorption lines consistently present in the wavelength range between 1220 and 1900 Å include the features at 1260, 1281, 1330, 1420, 1527, 1550, and 1640 Å. The 1260 and 1527 Å lines appear to be conventional interstellar Si II 1260 and 1527 absorptions, while the 1550 and 1640 Å features are probably stellar C IV and He II lines, consistent with the star's sdOB classification (see Fesen et al. 1988). The possible weak stellar Fe V absorption near 1464 Å is only marginally present in the 1988 spectra. No other features in the spectrum as strong as the interstellar 1260 Å Si II line appear present.

As shown in Figure 1, the 1281, 1330, and 1420 Å features attributed to absorbing material associated with the SN 1006 have not changed substantially from 1982 to 1988. Although all six spectra are underexposed, these three lines show no equivalent width variations at the 50% level and probably at the 25% level. Possible minor changes in the 1330 Å feature mentioned by Fesen et al. are not confirmed. The only possible change observed is the 1420 Å feature which may have broadened somewhat during this time period (see Figure 1). However, none of the three absorption features show any change in their central wavelength.

As shown in Figure 3, the line identifications for these features remain essentially unchanged from those discussed by Fesen et al. The 1420 Å feature is probably the Si IV resonance lines at 1393 and 1403 Å redshifted by 5000 km s⁻¹; the 1330 Å feature can be interpreted as a blend of Si II 1304 at 5200 km s⁻¹, O I 1302 at 6500 km s⁻¹, and interstellar C II 1335; and finally, the strongest feature at 1281 Å is most likely caused mainly by the 1260 line of Si II redshifted at a velocity of 6200 km s⁻¹, i.e. close to the velocity inferred from the Si IV interpretation of the 1420 Å feature.

While the strong 1281 Å feature has not varied, the new 1988 observations in conjunction with the four previous spectra indicate that this feature is actually a blend of at least two lines; one centered near 1282 Å, and a slightly weaker one near 1277 Å. Despite the low signal to noise near the bottom of such a strong absorption feature, 5 of the 6 individual spectra suggest an unresolved blend of at least two components. The other spectrum shows a broad line profile consistent with the blended profile seen in the five other spectra. Fesen et al. (1988) concluded that while most of the 1281 feature was likely due to Si II, about 25% or so might also be redshifted S II lines (1251, 1264, 1259) at a velocity of 6000 km s⁻¹. For this feature to be a blend, either there must exist two absorbing regions of Si II along the line-of-sight, or S II absorption must be present at a more substantial intensity.

The lack of changes in these lines implies a minimum dimension of 0.06 pc (for d = 1.7 kpc) for the absorbing gases, but leaves open the question, discussed by Fesen et al., of whether the Si, S, and O absorbing material is unshocked ejecta, or shocked ejecta which has cooled and condensed into knots. This is an important issue for it is not yet clear whether Type Ia supernovae produce the type of clumpy ejecta seen in young supernova remnants such as Cas A.
Figure 3
1988 IUE data (solid line) compared to 1986 data (dotted line) for the strong absorption features in the spectra of the S-M star. Data shown have been wavelength shift-corrected and smoothed by a three-point box-car function. Red-shifted positions of Si II, S II, O I, and Si IV are shown with relative oscillator strengths indicated by the lengths of the vertical lines. These plots are similar to Figure 8 of Fesen et al. (1988). Note the similarity of the absorption features seen in the 1988 data to that of the previous epoch data.
and the Crab Nebula. Knots in supernova ejecta may form as a result of thermal instabilities either at the time of the explosion or in reverse shocked ejecta.

The absence of variability in these lines is at least consistent with smoothly distributed unshocked ejecta. Calculations by Hamilton and Fesen (1988) indicate that any unshocked silicon should show comparable amounts of Si II and Si IV as the present time, as is observed. The Fe II absorption profiles indicate that the reverse shock lies not much beyond the 5000 km s\(^{-1}\) free expansion radius. Our identifications of absorbing material at higher velocities, namely S II at 6000 km s\(^{-1}\) and O I at 6500 km s\(^{-1}\), are uncertain because of possible blending; for example, the 1330 O I feature might instead be Si II 1304 at 5200 km s\(^{-1}\) and interstellar C II 1335 (see Wu et al. 1983). If the S II and O I line identifications are incorrect, then it is possible that no absorbing material has yet reached the reverse shock.

On the other hand, if the absorbing regions are composed of material shocked by the blast wave's reverse shock, then the combination of low ionization and high velocity requires the absorbing material to be condensed knots of ejecta. Clumpy ejecta would be consistent with the lack of any blueshifted absorption despite the symmetry of the Fe II absorption profiles. If our identifications of S II at 6000 km s\(^{-1}\) and O I at 6500 km s\(^{-1}\) are correct, then the absorbing material must lie far ahead of the unshocked iron, in the form of shocked and cooled knots. The velocity dispersion of several hundred km s\(^{-1}\) indicated by the width of the Si IV 1420 Å feature is comparable to the velocity dispersions seen in the reverse shocked metal-rich knots of Cas A.

Unshocked ejecta will produce slowly changing lines, whereas small knots of shocked ejecta should produce more rapid variations. The most decisive evidence in favor of knots would be rapid absorption line variability. However, until such changes are observed, the question of the structure and composition of this 1000 yr old Type Ia's ejecta remains uncertain.

IV ACKNOWLEDGEMENTS

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REFERENCES

X-ray & Cataclysmic Binary Systems
1. INTRODUCTION

Before the discovery of black holes it was argued that they should show up in the UV band (see e.g. Shvartzman, 1971). However, until recently, even after the discovery of a number of candidates, the bulk of information on the black hole itself, or more specifically on the gas accreting onto the hole, was derived through other spectral bands. Still the contribution of UV information is important for a global understanding of the systems hosting the black hole, and it is now becoming clear that, for some of them, the UV band can be of fundamental importance for constraining models of the class.

The stellar mass black hole candidates observed in the far UV are reported in Table I. They represent all the best candidates known thus far (see e.g. McClintock, 1986, and Ilovaisky, 1987). All of them, but SS 433, which is heavily reddened, have been detected in the far UV. A0620-00, was observed with the ANS satellite during X-ray flaring. For Cyg X-1, LMC X-1, and LMC X-3 the data derive from 10 years of successful IUE observations.

In this paper we first review briefly the observations of the two sources which have a massive non collapsed component, namely Cyg X-1 and LMC X-1. Then we consider A0620-00 and LMC X-3, whose visible component is much less luminous. The discussion will be focussed in particular on the latter object, because of its non-transient nature, and the important role of UV observations in clarifying the nature of the accretion disk around the hole.

2. MASSIVE X-RAY BINARIES:
Cyg X-1 and LMC X-1.

In both Cyg X-1 and LMC X-3 the optical luminosity of the non collapsed component exceeds the X-ray luminosity (see Table I). Because of their spectral type (O9.7ab for Cyg X-1 and O7-9 III for LMC X-1), the stars should contribute the most part of the UV emission as compared to that of the disk. In fact there is no photometric evidence of a disk in either system, and if the mass transfer occurs through a wind it is even dubious whether a disk could form.

In the case of Cyg X-1, UV absorption lines in the stellar wind are a direct probe of X-ray emission, which is supposedly produced in the inner regions. In fact the ionization state of the wind is strongly influenced by the X-ray emission. The formation of a ionization cavity in the wind of the primary, which should produce an orbital modulation of resonance lines, was considered theoretically by Hatchett and McCray (1977) and observed immediately after the launch of IUE in Cyg X-1 and Vela X-1 (see Dupree et al 1978, 1980; Treves et al, 1980). Modulation of Si IV and C IV is illustrated in Fig. 1. From a detailed application of the Hatchett and McCray model, Davis and Hartman (1983) were able to constrain the inclination angle of Cyg X-1 (36° < i < 67°). The phenomenon of line modulation by the ionization cavity appears rather similar in Cyg X-1 and Vela X-1, independently of the fact that the collapsed object is, respectively, a black hole and a neutron star. Other relations between X-ray emission and UV spectrum have been searched for in Cyg X-1, with particular reference to the appearance of X-ray dips (Pravdo et al, 1980), but none was found. Of importance could be the observation of UV absorptions during a high state of the X-ray source, but to our knowledge this was never done.

The UV continuum of LMC X-1 is typical of a star of its spectral type. In particular from the absolute luminosity no indication of an undermassive primary is found (Cowley et al, 1987). No orbital absorption line modulation, analogous to that of Cyg X-1 is observed in LMC X-1 (Bianchi and Pakull, 1985; Cowley et al, 1987). This is consistent with the non wind UV spectral lines. However some of the detected continuum variation can be induced by X-ray irradiation of the primary.

3. A0620-00

A0620-00 is an X-ray transient which at the epoch of its flaring (1975) dominated the X-ray sky, and remained active for several months. The optical counterpart was recognized because of its brightening by e B = 8. After returning to quiescence the optical counterpart appeared as a K dwarf. A binary period P = 7.74, was determined by McClintock and Remillard (1986), together with a mass function f(M) = 3.2 M☉, which makes the system probably
TABLE I

<table>
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<th>Source</th>
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<td>6</td>
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<td>10^{-2}</td>
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<tr>
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<td>9</td>
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</tr>
<tr>
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<td>27</td>
<td>&lt; 5 $\times$ 10^{-10}</td>
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<td>2 $\times$ 10^{-2}</td>
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</tr>
</tbody>
</table>

* flaring phase

7) Treves et al 1987  8) Treves et al 1988

Fig. 1. Equivalent width vs orbital phase in Cyg X-1 (from Treves et al. 1980)

Fig. 2. Dereddened UV energy distribution of A0620-00 in the flaring state; a black body distribution is fitted to the data (from Wu et al, 1976).

The clearest black hole candidate known thus far.

The 1500 to 3300 Å energy distribution was measured with the ANS satellite (Wu et al., 1976), during the explosive X-ray event. After correction for extinction, the energy distribution appears close to a black body with $T \approx 28000$ K (see Fig. 2). Wu et al. (1976) interpreted the UV emission as mainly due to the heating of the non-collapsed component, rather than to the accretion disk. A difficulty may be the absence of a single wave light curve at maximum activity, unless the inclination angle for the system were very small.
4. LMC X-3

Evidence of the black hole nature of LMC X-3 was found by Crampton et al (1983) who measured a binary period \( P = 1.7^{\pm} \) of the B3 V optical counterpart and a mass function \( f(M) \sim 2.3 \, M_\odot \). The X-ray spectrum is rather soft and the flux varies secularly by factors \( 10^2 \) (e.g. White and Marshall, 1984; Treves et al, 1988). In the visible it varies irregularly between \( V = 17.5 \) and 16.8. This is considered as evidence of a variable accretion disk contributing substantially to the optical emission (van der Klis et al, 1983). The irregular variability is superposed to an orbital modulation of double wave shape, supposedly due to ellipsoidal modulation of the optical component of \( V = 17.5 \) (Van Paradijs et al, 1987).

IUE observations were performed by us in 1986 and 1987 (Treves et al, 1986, 1987, 1988b). At the epoch of the latter observation quasi-simultaneous optical and IR coverage was obtained (see Table 2). The IUE spectra are reported in Fig.3. A substantial variation (60%) between the two observations is apparent.

The low state (1986) can be accounted for as emission of the optical star. In fact the UV data (plus V and B magnitudes corresponding to the lowest state of the source) are well fitted by a Kurucz model for a B3V star ( \( T = 19000 \) \( K \), \( \log g = 3.7 \)) assuming a reddening \( A_V = 0.2 \) and \( A_{\text{bol}} = 0.1 \) (see Fig.4). The energy distribution for the 1987 high state is reported in the same figure, and is interpreted to be dominated by disk emission. In Fig.5 the Kurucz model for the low state is subtracted from the primary. The result should represent the energy distribution of the sole accretion disk. As can be noted the spectrum increases with frequency in the optical band, and decreases in the UV, indicating that the emission peaks at 3000-3500 \( \AA \). A fit with a (reddened) black body appears rather satisfactory, yielding a projected area \( A_{\text{proj}} = 3.7 \times 10^{23} \text{ cm}^2 \) and a temperature \( T = 1.4 \times 10^4 \text{ K} \). From the value of \( A_{\text{bol}} \) an estimate of the inclination angle may follow, assuming that the disk dimension is given by the Roche lobe of the hole. This yields \( i = 50^\circ - 60^\circ \) (see Treves et al, 1988b).

If substantial X-ray heating of the disk is assumed, formation of a wind or a corona above the disk is expected (e.g. Begelman et al, 1983), and the resonance lines observed in the high state UV spectrum can reasonably be generated in this region.

![Fig. 3. IUE spectra of LMCX-3 (from Treves et al, 1988b)](image-url)
Table 2

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral range (Å)</th>
<th>Spectrum identifier</th>
<th>Obs. Date</th>
<th>Obs. Phase</th>
<th>Expose</th>
<th>Flux [erg cm⁻² s⁻¹ Å⁻¹]</th>
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<tbody>
<tr>
<td>UKE</td>
<td>2000-3200</td>
<td>JWP 7753</td>
<td>86 Mar 7 UT 04:15</td>
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<td>305</td>
<td>P(1550) = 4.6 × 10⁻¹⁵</td>
</tr>
<tr>
<td>UKE</td>
<td>1200-1950</td>
<td>SWP 27872</td>
<td>86 Mar 8 UT 05:56</td>
<td>0.47</td>
<td>291</td>
<td>P(1750) = 3.94 × 10⁻¹⁵</td>
</tr>
<tr>
<td>UKE</td>
<td>1200-1950</td>
<td>SWP 30159</td>
<td>87 Jan 9 UT 08:99</td>
<td>0.61</td>
<td>365</td>
<td>P(1750) = 6.53 × 10⁻¹⁵</td>
</tr>
<tr>
<td>UKE</td>
<td>3030-3200</td>
<td>JWP 2942</td>
<td>87 Jan 16 UT 07:42</td>
<td>0.71</td>
<td>163</td>
<td>P(3350) = 3.37 × 10⁻¹⁵</td>
</tr>
<tr>
<td>1.5m ESO</td>
<td>3050-3250</td>
<td>—</td>
<td>87 Jan 11 UT 04:00</td>
<td>0.69</td>
<td>48</td>
<td>P(1350) = 3.20 × 10⁻¹⁴</td>
</tr>
<tr>
<td>HC + IDS</td>
<td></td>
<td>3.6m ESO</td>
<td>87 Jan 8 UT 03:40</td>
<td>0.92</td>
<td>—</td>
<td>J = 16.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ KSnb</td>
<td></td>
<td></td>
<td>H = 17.1 ± 0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>K = 16.4 ± 0.3</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4.** Energy distribution of LMC X-3 in high and low state. The continuous curve is a reddened Kurucz's B3 V model (from Treves et al. 1988b).
5. CONCLUSIONS

UV observations yield information on the accretion onto black hole mainly because the UV radiation is produced by the interaction of the X-rays with the accreting material. As from variability studies the dynamics of the accretion process can be reconstructed, simultaneous monitoring at UV, optical and X-ray frequencies are of the utmost importance. A collaborative program with the GINGA team is in progress for a simultaneous multifrequency study of LMC X-3.

6. REFERENCES


IUE SPECTROPHOTOMETRY OF THE ACCRETION DISK OF HZ HER/ HER X-1

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ABSTRACT

We present IUE low resolution spectra of the accretion disc of the X-ray binary HZ Her/ Her X-1. The UV flux contribution from the sub-giant companion HZ Her was predicted, using a model constrained by fits to B-magnitude photometry, and subtracted from the observed IUE spectra to leave accretion disc spectra. We compare the observed disc UV fluxes with those predicted by a simple model of the disk emission based on X-ray reprocessing.

Keywords: IUE, HZ Her/ Her X-1, Accretion Disks.

1. INTRODUCTION

The periodic variations in the X-ray, optical and UV fluxes observed from the X-ray binary HZ Her/ Her X-1 are best explained by a roche lobe-filling primary (HZ Her) transferring material via a tilted, 'processing', accretion disk to the magnetic poles of a neutron star secondary (Her X-1) (Refs. 1 and 2). This explains the observation of pulsed ($P_{\text{pulse}} = 1.24$ sec) X-rays from Her X-1, which are reprocessed in the accretion disk and the heated hemisphere of HZ Her which faces Her X-1 to give optical pulsations with a similar period. Also, the periodic obscuration of our line of sight to Her X-1 by the accretion disk gives rise to the observed 35-day X-ray cycle.

The UV flux from the system arises mostly from the reprocessing of X-rays in the accretion disk and heated hemisphere of HZ Her. The intrinsic (i.e. if there were no X-ray heating) UV flux from HZ Her is very low (it is barely detected by IUE), as would be expected of an A9-type star with $m_B = 14.5$. This means that observations carried out by IUE at orbital phases $\phi = 0.0$ since, at these phases, the heated hemisphere of HZ Her is turned away from us so that the contribution from HZ Her to the IUE spectra is comparatively small. This means that any errors in the accretion disk fluxes arising from the subtraction of imperfectly modelled stellar fluxes will be negligible for $\phi \sim 0.0$. We have avoided data where the disk itself is totally eclipsed.

The most important parameters adopted or derived from the fits to the optical photometry may be summarised as:

$$M_{\text{Her}X-1}/M_{\text{HZHer}} = 0.00$$

$$i = 85^\circ.3$$
binary separation = 6.34 × 10^{11} \text{cm}

Earth – system distance = 1.87 × 10^{22} \text{cm}

HZ Her radius, \( R_a = 2.7 \times 10^{11} \text{cm} \)

disk radius = 2.0 × 10^{11} \text{cm}

disk half – height, \( H = 2.1 \times 10^{10} \text{cm} \)

\( \alpha = 9^\circ.8 \)

3. MODELLING THE ACCRETION DISK

Having isolated the accretion disk spectrum, we attempt to match it using a slightly more elaborate model than used in the initial fitting procedure. The disk is now assumed to be made up of \( N \) concentric, coplanar, cylindrical annuli of height \( 2H \). The innermost annulus is of radius \( R_{in} \), equal to the Alfvén radius. The outermost annulus is of radius \( R_{out} \), which was found from the model of the flux contribution from HZ Her. The flux \( F(R) \) (integrated over all wavelengths) emitted by an annulus at radius \( R \) is assumed to be given by a simple power-law, i.e.,

\[
F(R) = C . R^{-\beta} \tag{1}
\]

where \( C \) is a constant which relates the incoming X-ray flux to the outgoing flux for all the annuli. If \( H \ll R_{out} \) and \( \beta \neq 2 \), then

\[
C = \frac{(H/R_{out}) . \varepsilon L_x . (2 - \beta)}{2 . \pi . (R_{out}^2 - R_{in}^2)} \tag{2}
\]

where \( \varepsilon L_x \) represents the efficiency with which X-rays are reprocessed multiplied by the X-ray luminosity of the neutron star. If \( \beta = 2 \) then

\[
C = \frac{(H/R_{out}) . \varepsilon L_x}{2 . \pi . \ln(R_{out}/R_{in})} \tag{3}
\]

We assume that the disk is optically thick at all wavelengths, so that the effective temperature of an annulus, \( T_{eff}(R) \), is obtained from equation (1) as

\[
T_{eff}(R) = (C/\sigma)^{1/4}.R^{-\beta/4} \tag{4}
\]

and we can calculate the blackbody flux from each annulus: \( B_{\lambda}(R) = B_{\lambda}(T_{eff}(R)) \). Each annulus was assigned the same width \( dR \). The blackbody emittance \( E_{\lambda} \) from the disk is thus given by summing over all annuli to obtain

Figure 1. Mean disk fluxes in the wavelength range 1810 Å to 1900 Å plotted as a function of 35-day disk phase \( \psi \). The disk is maximally open when \( \psi = 0.14 \). Filled circles: disk totally eclipsed by HZ Her; open circles: disk partially eclipsed by HZ Her; crosses: disk unclosed. Spectra obtained when the heated hemisphere of HZ Her was in opposition have been excluded, since these are more affected by inaccuracies in our model's prediction of the UV flux from the heated hemisphere.
The specific flux $F_\lambda$ observed at Earth is given by

$$F_\lambda = E_\lambda \cos k/(4\pi D^2)$$

where $D$ is the Earth-system distance and $k$ is the angle between the observer's line of sight and the disk normal, given by

$$\cos k = \sin i \sin a \cos (2\pi (\psi - 0.14)) + \cos i \cos a$$

where $i$ is the system orbital inclination and $a$ is the angle between the disk normal and the orbital plane normal.

The model includes a contribution from the disk edge: $T_{\text{eff}}$ at the edge is assumed equal to that of the outermost annulus.

Eclipses of the disk were modelled by using a spherical occulting body with radius equal to the side-radius $R_B$ of the Roche lobe which HZ Her is presumed to fill.

The results presented in this paper were obtained from a model for the disk consisting of 1000 annuli, each consisting of 64 sectors for eclipse modelling purposes.

4. DISCUSSION

We found that $\beta = 2.0 \pm 0.5$ gives a good fit to the data. From figure 1, a plot of IUE photometric observations of the accretion disk as a function of disk phase, we can see that there are two maxima in the light curve. The larger one peaks around $\psi \approx 0.14$, which corresponds to the disk being maximally open as viewed from Earth, so that we have a relatively unimpeded view of the innermost parts of the disk. The peak of the smaller maximum is harder to ascertain, but the fact that it is smaller and broader suggests that $i$ must be less than 90° and that $a$ must be greater than zero, so that we see more flux when the disk is slightly offset from the 'viewed from below' orientation at $\psi \approx 0.64$.

Figure 2 shows the effect of disk orientation on the observed IUE fluxes. It can be seen that the disk model predicts reasonably well the fluxes observed both when the disk is fully open ($\psi \approx 0.14$) and when the disk is viewed from below ($\psi \approx 0.64$).

Figure 3 illustrates an eclipse of the disk by HZ Her. Both observations were made at essentially the same disk phase. The upper curves show an observation and model of the disk when the outermost 25 (out of 1000) are partially eclipsed, the rest of the annuli are partially eclipsed. It can be seen that the model overestimates the flux from the more eclipsed disk. This may be because we have overestimated the radius of the disk, or because the value of $\beta$ in the outer part of the disk actually increases.
Figure 4 shows the observed and predicted fluxes when \((\psi - 0.14) \sim 0.75\), when any departures from azimuthal symmetry would be expected to cause the maximum discrepancy between observation and model. It is evident that the model predicts too much flux at the shortest wavelengths, indicating that the hot inner region of the disk may be shielded by some azimuthal structure in the real disk.

5. HZ HER: STILL ACTIVE IN JANUARY 1988

The IUE FES was used on 1988 January 27th U. T. 08hrs 13min, when \(\phi = 0.700\) and \(\psi \approx 0.05\), to measure \(m_B = 13.3\) (corrected for FES sensitivity variations). This matches our model prediction, indicating that X-ray heating of HZ Her and the accretion disk is continuing as normal.

6. ACKNOWLEDGEMENTS

We thank the ground staff of the Vilspa IUE tracking station. Dr. J. C. Raymond obtained many of the observations at Goddard. We thank Drs. Deeter and Boynton for the use of their optical photometry. SJB acknowledges the support of a SERC studentship.

7. REFERENCES

SIMULTANEOUS IUE, EXOSAT, AND OPTICAL OBSERVATIONS OF THE UNUSUAL AM HER TYPE VARIABLE H0538+608

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ABSTRACT

We report on simultaneous observations of the AM Her type variable H0538+608 made with IUE, EXOSAT, and the 1.3 m McGraw-Hill Observatory telescope. Subsequent optical spectrophotometry at high and low resolution was also performed. The X-ray and optical data show clear evidence of a 3.30±0.03 hour period. Three SWP spectra were taken outside of eclipse and during overlapping phase intervals. The UV spectra contain strong emission lines characteristic of this class of objects and a flat continuum which appears to be deficient, given the brightness of source at optical and X-ray wavelengths. There is evidence for intensity variations in emission lines, particularly CIV. The X-ray light curves for H0538+608 reveal some interesting behavior which may be related to irregularities in its accretion flow.

Keywords: X-ray Binaries, Cataclysmic Variables

INTRODUCTION

AM Her type objects are widely believed to consist of a magnetic white dwarf in synchronous rotation with a late type secondary and with magnetically channeled accretion flow onto the white dwarf. They are characterized by substantial optical polarization modulated at the orbital period, rapid optical flickering as well as periodic photometric variations, strong emission lines, UV excess and X-ray emission. They tend to be faint with periods are on the order of hours (Ref 1). Most are not phase resolvable with IUE.

The X-ray source H0538+608 (also 4U0541+60, Ref. 2 and 1H053+607, Ref. 3) was identified with a V=14.6 blue (U-B=-0.81) object using positional information from the HEAO A-3 modulating collimator experiment (Ref. 4). Its optical spectrum was found to contain broad emission lines of H, HeI and HII. Photometric variations were modulated at the nominal 3 hour period as were measurements of circular polarization. These properties are all characteristic of AM Her type CVs.

On day 281-2 (UT), 1985 a comprehensive program of optical, X-ray and UV monitoring of H0538+608 was carried out. This report is a presentation of the data obtained with IUE and a preliminary discussion of its implications. Parts of the optical and X-ray are also presented.

2. OBSERVATIONS AND DATA ANALYSIS

Since the cataloged X-ray intensities for H0538+608 are comparable to AM Her itself and since we expected the UV continuum to scale to optical and X-ray fluxes in a similar manner we expected to be able to obtain well exposed SWP spectra in 30 - 45 minute integrations, i.e. much less than the three hour period. What we found however, was that this object was deficient both in its soft X-ray and UV intensity. Figures 1 and 2 show the 1150 - 2000 A (SWP) spectra obtained for H0538+608 and a composite X-ray, UV and optical spectrum. The integration times for the SWP spectra are 70, 100 and 50 minutes. The optical and X-ray points on figure 2 are for approximately quarter phase; the UV points are based on integrations outside of eclipse.
Figure 1. SWP spectra of H0538+608, (a) day 282, 1985 phase 0.1-0.4, (b) day 282, 1985 phase 0.5-1.0, (c) day 282, 1985 phase 0.2-0.5, (d) day 95, 1988 unknown phase

Figure 2. Composite X-ray, UV and optical spectrum for H0538+608

We had hoped to use the shape of the UV continuum as a function of phase to test the hypothesis that the net flux is a combination of cyclotron emission from the accretion column and the Rayleigh-Jeans tail of a black body. The latter would result from the reemission of hard photons off the white dwarf surface at the base of the accretion column (Ref. 5). This feature should appear as a steepening of the SWP flux as seen for example, in AM Her itself (Ref. 6) when the base of the accretion column is visible.

Since we do not have phase resolved spectra and owing to the low S/N of the continuum in each of the spectra we obtained, we cannot unambiguously rule out the presence of a Rayleigh-Jeans component. However, a power law in wavelength was fitted to two of the three spectra of day 282, 1985 by binning portions of the continuum containing no apparent features. The resulting power law indices were $-1.10 \pm 0.5$ and $-1.72 \pm 0.6$. This is consistent with the notion that the Rayleigh-Jeans component is absent. It also reflects the overall (flat) nature of the composite spectrum (figure 2).

As is the case with other AM Her objects observed by IUE the SWP spectra have a number of strong emission lines. The lines identified are NV(1240A), SiI(1302), SiIV(1394), CIV(1549), HeII(1640), and NIV(1718); table 1. Some of the emission lines are variable in intensity and some line ratios are variable. In particular, the CIV is nearly absent in one of the three SWP spectra of day 282, 1985 (SWP26900). This spectrum was the result of a 50 minute integration starting at about phase 0.2. Another spectrum, SWP26898, also covers this phase interval, but the CIV is clearly present. CIV is generally weak relative to the other lines when compared to other AM Her objects observed with IUE. Another notable feature of the SWP spectra of H0538+608 is the anomalously large (relative) strength of the NV feature, as first pointed out by Bonnet-Bidaud and Mouchet (Ref 7). This is more pronounced for the day 282, 1985 spectra than for the April 1988 spectra. The HeII feature appears broadened towards its blue wing on some of the spectra. In SWP26900, there is marginal evidence for a P-Cygni profile in HeII, although the data quality is poor.
The EXOSAT light curves (figure 3) have several notable features. The soft X-ray flux (LE; 0.2 - 1.0 keV) clearly shows intensity modulation with eclipsing at the 3.3 hour period. These effects also appear to be slight intensity dips at around phase 0.5. The duration of the eclipses seems to vary. The hard X-ray (ME; 1.0 - 8.0 keV) intensity does not show eclipsing. This type of behavior is similar to that seen in EF Eri, for which the eclipses are presumed due to obscurations of the magnetic polar cap (Refs. 8, 9). However, the ME light curve is rather erratic, particularly on day 281. It clearly shows aperiodic variation with surges by up to a factor of ~6. It is apparent from figure 3 that these are uncorrelated with the LE light curve. The ME hardness ratio does not reflect the intensity surges. The ME light curve of day 282 varies less dramatically than on day 281.

Most of the planned photometric monitoring of H0538+608 concurrent with the EXOSAT and IUE observations was lost to clouds. However, low resolution optical spectra taken during November, 1986 clearly show spectral modulation at one half of the orbital period (1.67 hours). The spectra alternate between a reddish continuum with weak emission lines and a bluish one with strong lines. November 1986 observations showed similar modulations, but at the full 3.3 hour period. This could be an indication that accretion to a second magnetic pole undergoes transitions between a high and low state.

Our preliminary interpretation of the X-ray light curves is that H0538+608 exhibits accretion flow variability on time scales less than the orbital period. These instabilities could be a variable accretion rate or distortions of the flow geometry. The latter case would involve complex magneto-hydrodynamic effects with an entangling of the gas stream and magnetic field lines. One might reasonably expect these type of phenomena to be evident in the UV. The broad emission lines seen by IUE are believed to originate in the base of the accretion column (eg. ref. 5). The UV continuum is probably also variable, but it is beyond the capability of IUE to study this system on the required time scale. However, several possibly related effects are seen in the IUE data.

The emission line intensities for H0538+608, particularly CIV are variable. Line ratios as well as individual intensities show variability. It has been pointed out by Bonnet-Bidaud and Mouchet (Ref. 7) that the NV feature is anomalously strong relative to other lines. They suggest that this may be indicative of non-solar abundances such as produced in nova-type outbursts. H0538+608 may be representative of some short term evolutionary stage for this class of objects. The classical nova V1500 Cyg has been identified as an AM Her type CV with non-synchronous rotation (Ref. 10). It is possible that non-synchronism could cause accretion instability if the angle between the magnetic and spin axes is sufficiently large. Although there is no direct evidence of asynchronous rotation in H0538+608, we cite the possibility of a connection between its erratic high energy behavior, its anomalous abundances and the system V1500 Cyg.
3. DISCUSSION

H0538+608 appears to have several unique characteristics among AM Her type objects studied. It has a high X-ray to optical luminosity ratio, yet it has a relatively flat spectrum and surprisingly low UV continuum luminosity. The emission lines observed by HUE are variable, with CIV being virtually undetected in one SW spectrum. Its X-ray light curves display an erratic behavior which may be indicative of either a variable accretion rate or distortions of the accretion geometry on time scales less than the orbit period. Optical data taken about one month later show a spectral modulation as well as intensity modulation at one half of the orbital period. Later optical monitoring shows modulation at the orbital period indicating that one pole may exhibit high/low states.

The X-ray light curves and the optical data of November, 1985 are atypical of AM Her objects. The SNR spectra also have unusual characteristics. Could H0538+608 be representative of some transient evolutionary state? We speculate on a possible link between the type of behavior seen in H0538+608 and the system V1500 Cyg. In subsequent work, using additional data we plan to address this issue in more detail.

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The transient X-ray binary system A 0535+26/HDE 245770 has been extensively monitored at different wavelengths since its discovery as X-ray emitter. These coordinated observations enabled us to find correlations in the variability of the optical and X-ray emissions. Moreover, during some activity periods of the system, UV discrete absorption components in Si IV and C IV resonance lines have been detected, whose velocities vary between -300 and -600 km/s. The study of the narrow absorption components at the expected activity epochs (periastron passages of the neutron star) simultaneously with X-ray, optical and IR observations has been essential for a better knowledge of both the wind structure of the Be star and its interaction with the neutron star.

In this paper we emphasize the study of the physics and dynamics of the mass transfer at periastron and subsequent X-ray flaring, which is a typical problem of the X-ray/Be binary system class.

1. INTRODUCTION

The massive X-ray binary A 0535+26/HDE 245770 is one of the group of X-ray/Be systems. This system – a hard X-ray pulsar with spin period of ~104 s (Ref.1) and an O9.7 IIb star (Ref.2) and orbital period of 111 days (Ref.3) – has been extensively monitored, starting soon after its discovery as X-ray emitter, in various wavelength regions (Refs.4,5). The most recent review of this system, together with a compendium of its characteristics can be found in the Refs.4 and 5. In this paper we present the multifrequency picture of this system, emphasizing the behaviour of the optical component HDE 245770, mainly referring to our measurements, spread in twelve years, made mostly with IUE satellite and Loiano telescopes, for a total of several hundreds spectra and almost one hundred nights of UBV photometry.

2. THE MULTIFREQUENCY PICTURE OF A 0535+26/HDE 245770

2.1 THE X-RAY PICTURE

A 0535+26 is normally an extremely weak X-ray source (a few units of mCrab), under the threshold of detectability of most X-ray detectors. Sometimes it flares-up to some tenths of Crab (exceptionally to about two Crab). This transient behaviour, though not strictly periodic, is probably correlated with the varying distance of the neutron star in an eccentric orbit from the "normal" hot massive star and completed in 111 days. During two periods (April 19, 1985 and March 17, 1986) in which X-ray flares-up were expected, following the ephemeris of Priedhorsky and Terrell (Ref.3), we detected only ~ 6.5 mCrab and < 5 mCrab, respectively, via ASTRON satellite (2-25 KeV). Also EXOSAT detected fluxes of few mCrab on March 9, 1986 as well as during the quiescent phases on February 10 and 19, 1986 and on September 25, 1985 (Ref.6). Table 1, not far to be complete, summarizes the X-ray observations of A 0535+26 in the real ranges of detection and reports also the fluxes in Crab units.

2.2 THE ULTRAVIOLET PICTURE

A long series of UV low and high resolution spectra in both wavelength regions (1200 - 1950 Å and 1900 - 3200 Å) has been taken with IUE, at VILSPA base, starting from Feb. 1980 to Jan. 1988 in order to determine the UV behaviour of HDE 245770 and the interaction parameters between the Be star and the neutron star (i.e. temperature, energy distribution, mass loss, etc.).

No sensible variations in the UV fluxes and in the terminal velocity have never been detected in various epochs and in different X-ray states. So that, we can confine the values of ~ 650 km/s, as terminal velocity and the mass loss rate of ~ 10^{-8} M_{\odot}/yr (Refs.7-9). On the contrary,
observed in the occasion of the X-ray outburst 245770 binary ayntem was comprehensively described in the section 2.3.

The optical picture

2.2. PHOTOGRAPHIC

The historical B light curve, reported for the first time by Stier and Liller (Ref.17), furtherly up-to-date by Guarnieri et al. (Ref.18), has been completed with our measurements taken at Loiano 60 cm telescope up to March 19, 1988. It is reported in Fig. 1.

Table 1. Summary of X-ray Observations of A0535+26 in Outburst and Quiescence. The references, up to 1986a, cited in the table can be found in Refs. 4 and 5. The other are: Giovannelli et al., 1986b, IAU Circ. N. 4256. Giovannelli et al., 1986, IAU Circ. N. 4386.

discrete absorption components in Si IV and C IV resonance lines, found to be ubiquitous in Be stars (Ref.10,11), have been seen in one series of spectra (Jan. 1984), with velocities near 300 Km/s and near the terminal velocity (650 Km/s) (Ref.12). The component observed are probably formed by blobs of material ejected near the equatorial plane of the O9.7 IIIe star and can indicate a variable mass loss superimposed on a steady wind. No narrow absorption components were observed in the occasion of the X-ray outburst event of Nov - Dec 1981, whose maximum was reached on Dec 13. This event was extensively watched in the visible (a complete description will be published promptly) and will be briefly described in the section 2.3.

2.3 THE OPTICAL PICTURE

2.3a SPECTROSCOPY

The luminous companion of the A 0535+26/HDE 245770 binary system was comprehensively classified as O9.7 IIIe by our group (Ref.2) and later confirmed by other groups (Ref.13,14).

In spite of the scarcity of rotationally enlarged features in the blue spectrum of HDE 245770, its BO characteristics are definitively not questionable. The luminosity class is a bit more uncertain being the evaluation of Hutchings' group up to V. We believe that the luminosity class is III as commented in our later papers (Ref.9,4).

Emission lines are always present in our twelve-years series of spectra ranging from ~3400 to ~7000 A, but both the equivalent widths and originating elements are largely variable, as usual in Be stars. HÎ¿ in emission is a permanent feature, however its equivalent width has changed at least a factor of ~10 among our observations. HÎ¿ variable emission is almost, but not always, present. HÎµ emission seems to be correlated with the X-ray major activity; during quiescent X-ray phases, this line is either filled-in or in (weak) absorption. Other Balmer lines are, normally, either in absorption or filled-in. Also the He I lines 4922 A, 5876 A and 6678 A are sometimes in emission, but no obvious correlation with the X-ray activity was noted. He II (4686 A) emission line, typical of massive X-ray binaries with accretion disks, was never observed. Emission of several Fe II lines has been reported by some authors (e.g. Refs.15). They are normally absent in the spectrum. We observed an unique phenomenon of Fe II emission and redshifting during the Nov-Dec 1981 X-ray outburst: a sudden appearance of numerous strong Fe II lines in emission, on Nov 19, with velocities varying in a time scale of hours from 0 to 650 Km/s and, in the same night, decreasing to 250 Km/s. They had disappeared 3 days later (Ref.16).

2.2b PHOTOMETRY

The historical B light curve, reported for the first time by Stier and Liller (Ref.17), furtherly up-to-date by Guarnieri et al. (Ref.18), has been completed with our measurements taken at Loiano 60 cm telescope up to March 19, 1988. It is reported in Fig. 1.
From Fig. 1, it is possible to distinguish two photometric behaviour of HDE 245770: i) high stability in the range 1975 - 1981; ii) strong variations before 1975 and later 1981.

The beginning and the end of the high photometric-stability phase roughly occur in coincidence with the strongest April 1975 X-ray outburst of A 0535+26 (Ref.1), and with the unusual spectral activity of HDE 245770 (Ref.19), respectively. Besides this secular variability, other kind of light variations have been detected during the twelve-years monitor, such as Be-like microvariability, flares, flickering due to the 104 s pulsed X-ray emission, and the modulation with the orbital period (Refs.20,21). Among these variations, the most exciting are the flares, detected in five cases, occurring either roughly one week before or in coincidence with the X-ray outbursts, near the periastron passages of the neutron star (Refs.22,9,4,23,24).

We want to remark at least other two behaviour of the system during the high stability photometric phase: i) Hα and Hγ in emission are more intense than during the strong photometric variation phase; ii) the Be star is redder when it is more luminous (Refs.14,18). This is valid both on long time scales (years) (Fig.1) and on short time scales (days) (Refs.25,9). Among our results, for example, HDE 245770 showed a Vmag = 8.96 and B - V = +0.55 on Oct 28, 1980, while a Vmag = 9.07 , B - V = +0.49 on Sept 14, 1987 and Vmag = 9.02, B - V = +0.51 on Sept 20, 1987, being the errors of the order 0.01 mag.

These facts can be interpreted, within the classical Be star models, as due to the formation of an equatorial envelope seen at an orbital inclination angle less than 60 deg.

Since during the high stability photometric phase, many X-ray strong outbursts occurred in the system, it is difficult to find direct, easy correlations between the long term optical behaviour of the Be star and the X-ray behaviour of A 0535+26. These correlations, on the contrary, can be found looking at both the short term optical variations and spectroscopic features of the Be star.

3. DISCUSSION AND CONCLUSIONS

The behaviour in the ultraviolet, optical and infrared wavelength regions of the A 0535+26/HDE 245770 system is dominated by the Be star. The contribution of the neutron star to the optical activity of the system could only be individuate in some minor - but very interesting! - features, such as a periodic low-amplitude enhancement of the luminosity at the phases near the periastron and the presence of travelling blobs of matter, possibly revealed either by narrow absorption components in the wings of Si IV and C IV UV resonance lines or by the sudden redshifting of some optical Fe II lines.

The most astonishing feature in Fig. 1 is certainly the plateau of the luminosity that the system kept perfectly constant (with the exception of the short-time scale variabilities (Ref.20)) during almost six years, from 1975 to 1981. In that period HDE 245770 could have been used as standard luminosity star! This fact could be the key for a deeper comprehension of the physics of the system.

Actually, that optically quiescent phase of the Be star is characterized by these other behaviour:

a) maximum intensity of optical luminosity;

b) maximum intrinsic reddening of the star, clearly correlated with the luminosity variations;

c) high (variable) intensity of the emission lines in the optical spectrum;

d) the greatest X-ray outbursts ever observed in this system.

These features are not exclusive of that optically quiescent phase of the Be star, but their concurrence must be explained in a coherent manner.

We tentatively assume this following rough picture: i) a major envelope ejection at the mid of the seventies; ii) dissipation of the envelope accomplished in 1981.

The phase i) should imply, as consequence:

i) high luminosity;

ii) high reddening;

iii) high X-ray outbursts (because of the large amount of matter available for the accretion onto the neutron star);

iv) high stability of the optical luminosity (because of the screen effect of the envelope on the "normal" activity of the Be star).

The phase ii) should be characterized by:

A) a fading of the luminosity;

B) a fading of the emission lines intensity.

These are just the characteristics we observe after the optically quiescent phase. As example, typical values of the equivalent widths (EW) of Hγ and Hδ in emission are, during 1986, 16 A and 0.9 A, respectively, while on Jan 31, 1988, the prevailing features of the spectrum are absorptions of most H and He lines; Hδ is filled-in, and only Hα is in emission, being its EW = 2 A. However, this value, as well as the light intensity, are night-to-night variable, showing the usual activity of the Be star going on.

What about the neutron star? It is a useful indirect probe of the behaviour of the region surrounding the Be star, and much more powerful in a phase as i). The recent discovery that in X Per the optical continuum shows the same pulsed period as in the X-ray range (Ref.26) renews the hope that also in HDE 245770 an optical pulsed period of ~104 s could be detected, during the strongest X-ray outbursts of A 0535+26, near the superior conjunction. Up to now, no positive detections have been performed - probably either because of the no coincidence of the fast photometric measurements with the superior conjunction during strong X-ray outbursts, or because of the intrinsic impossibility to detect this optical pulsed period due to the morphology of the system - with two exceptions: i) in the EW of Hα lines, which showed once a periodicity of ~104 s (Ref.27); ii) in the photoelectric photometric data of Korakitis' Ph.D. thesis (Ref.28), also reported in Ref.4.

So, in order to solve, definitively, without ambiguity, the problem of the interaction of the neutron star with the Be companion, we have planned and organized, within this year, a deep multifrequency (from X-ray to IR) survey of A 0535+26/HDE 245770 near the periastron passage of the system, by using X-ray ASTRON and UV IUE satellites, Loiano 1.5 m and 0.6 m and Haute Provence 1.5 m optical telescopes, and the CNR IR telescope of the Cornerot Observatory.
4. REFERENCES

IUE AND OPTICAL OBSERVATIONS OF X-RAY SOURCES IN THE LMC.

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ABSTRACT

The optical counterparts of LMC X-6 (star Wo564) and of LHG-8 (HV5542) were observed with IUE and with several optical instruments at ESO.

We present the analysis of the UV spectral features and continuum flux, from which the values of the effective temperature and bolometric luminosity of the stars are derived.

We also analyze a number of UV and optical observations of the source LHG-83, obtained over the past three years.

Key words: X-ray binaries, optical spectra, hot stars.

1. INTRODUCTION

The X-ray sources in the Magellanic Clouds are particularly interesting as there is evidence that the properties of the hot stars and X-ray systems in the MCs are different from galactic objects of similar type, possibly indicating a different type of stellar evolution. Few MC's binaries have been observed in the past with IUE: e.g. LMC X-4 and SMC X-1 (van der Klis et al.1982, ref.9), LMC X-1 and Sk-70 36(Bianchi and Pakull, 1984, ref.1), Hutchings et al. 1987-ref.6, Bianchi and Pakull, 1985-ref.2). From Einstein HRI and IPC positions, and follow-up EXOSAT work, and optical observations (see e.g. Pakull, 1984-ref.8) a good number of other sources could be firmly identified. Some candidates are very faint but others could be observed with IUE with good S/N.

We present observations of two very early type stars with almost no reddening, and new observations of LHG83.

2. W0564=LMC X-6

This object was observed at low dispersion with both IUE cameras (images SWP24517 and LW43518), and at optical wavelengths.

The UV spectrum, shown in Figure 1, does not show any 220nm absorption, indicating little or zero reddening. Without any reddening correction, the UV spectrum is very well represented by a model atmosphere with $T_{eff}=25000K$, $log g=3.5$ and the observed flux at the Earth, using the bolometric correction of the best fit model and a distance modulus to the LMC of 18.4, would translate into a luminosity of $logL/Lo=4.2$. These parameters would be consistent with a spectral type B1V-V.

However we know that there is at least a foreground reddening of $E(B-V)=0.05$ in the direction of the LMC. By correcting the spectrum for this value, we obtain a best fit model $T_{eff}$ value of 35000K, $log g=3.5$ and $logL/Lo=4.7$, roughly consistent with a spectral type between O8.5 and O9.7V. From the analysis of the UV lines (details will be published elsewhere) e.g by comparison with the galactic standard stars IUE atlas (Wu et al.1983) a spectral type around O9-9.5, class IV-V is inferred. It is known however that LMC stars have weaker resonance lines than galactic stars, and comparing the equivalent width of the CIV line at 1550Å (3.6Å) with the LMC sample of Hutchings (1982-ref.5) W0564 could be classified around B0. Since the Hutchings (1982-ref.5) sample contains mainly supergiants, it is likely that W0564 is somewhat earlier than B0.

2. HV5542=LHG 8

Also for HV5542 we obtained IUE spectra with the long and short wavelength cameras (LWP4357 and SWP35458), which are shown in Figure 2. After correction for the foreground reddening, the UV continuum is best fitted by a model atmosphere with $T_{eff}=20000K$ and $log g=3$. Extrapolation, with this model atmosphere, of the observed flux to the visual band, gives $V=14.6$ and $M_{bol}=-5.94$, corresponding to $logL/Lo=4.3$. The Teff and L values are consistent with a spectral type B1.5-2III.

The UV lines, especially the SiIV and CIV resonance doublets, are much stronger than in W0564, indicating a higher luminosity class (the SiIV 1400 is a strong luminosity indicator, see e.g. Walborn 1984-ref.10).
Figure 1. The UV spectrum of Wo564: (top) the observed flux, (bottom) the flux dereddened with $E(B-V)=0.05$. The superimposed line is a model atmosphere with $T_{\text{eff}}=35000K$.

Figure 2. The UV spectrum of HV5542, dereddened with $E(B-V)=0.05$, and a model atmosphere with $T_{\text{eff}}=20000K$. 
3. LHG 83.

The X-ray source number 83 of the CAL Einstein survey of the LMC (Long et al.1981--ref.7) is identified with a faint (V=17) blue star (Pakull, 1984--ref.8; Cowley et al.1984--ref.3).

We have observed this object with IUE and in the optical over the past three years, and significant variability was detected at all wavelengths. An IUE spectrum of this source, with a detailed analysis of optical data, has already been published by Crampton et al. (1987--ref.4).

In Figure 3 our IUE SWP observations are shown, but for the analysis of the variability we have also obtained copy of the other spectra available from the IUE archive.

We note that our SWP observations obtained in Nov.1984 and Dec.1987 have fairly comparable flux levels, while in Jan.1987 the flux was higher by a factor from 2 to 3 through the SWP range, and the spectrum was hotter. Simultaneous observations obtained at ESQ (European Southern Observatory) in Jan.1987 indicated that the star was very much brighter also at optical wavelengths. The flux levels of the archive spectra are also lower than our Jan.1987 spectrum and rather comparable to our other two observations.

Strong line features, undetectable or very weak in the other observations, also appeared in the Jan.1987 spectrum. Among the strongest features, that can easily be seen in the Figure, there are the interstellar-like (circumstellar?) absorptions of SiII1260, OII1300, CII1335, and strong emissions at λ1240, 1403 and 1640, corresponding to NV, SiIV, and HeII. By combining the spectra at UV and optical wavelengths, it seems that the flux can not be interpreted as pure stellar emission, but rather in terms of an accretion disk. A detailed modeling is in progress.

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THE ANALYSIS OF SPECTRA OF NOVAE TAKEN NEAR MAXIMUM

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ABSTRACT

We have recently begun a project to analyze ultraviolet spectra of novae obtained at or near maximum optical light. These spectra are characterized by a relatively cool continuum with superimposed permitted emission lines from ions such as Fe II, Mg II, and Si II. In contrast, the spectra obtained late in the outburst show only emission lines from highly ionized species and in many cases these are forbidden lines. These ultraviolet data will be used in combination with recent calculations of spherical, expanding, stellar atmospheres for novae to determine elemental abundances by spectral line synthesis. This method is extremely sensitive to the abundances and completely independent of the nebular analyses usually used to obtain novae abundances.

1. Introduction

The initial eruption of a nova is very rapid, with the major part of the rise to visual maximum taking place in a day or less. During the rising branch of the light curve, the nova basically consists of an optically thick, uniformly expanding shell. As the expansion is very rapid and the luminosity fairly constant, the effective temperature smoothly declines and reaches a minimum of 4000K-7000K at visual maximum (e.g., Gallagher and Ney 1976; Gallagher and Starrfield 1978). At this time the material, which is mostly hydrogen (except in some very unusual novae), begins to recombine and the pseudo-photosphere begins to move inward in mass. In fact, as has been emphasized by Gallagher and Starrfield (1978), the optical maximum is purely an opacity effect caused by the large decrease in opacity when hydrogen recombines.

It is only during this time that pure absorption line or P-Cygni profiles are seen and are accessible to analysis (Williams et al. 1981; Starrfield 1987). In fast, optically luminous, novae the primary shell will become optically thin in a few days; thereafter, the optical spectral region is dominated by bremsstrahlung and hydrogen bound-free emission (Gallagher and Ney 1976; Ennis et al. 1977; Martin 1987). However, because the ultraviolet opacity is higher, the ultraviolet region of the spectrum remains optically thick for a much longer period and the continuum can be present for days to weeks. The cause of the enhanced ultraviolet opacity is the presence of thousands of lines from the astrophysically abundant elements such as iron and magnesium and other elements with similar atomic structure. In other astrophysical environments this is called the "iron forest".

In a slow (low optical luminosity) nova, such as Nova Vul 1984 #2, continuous mass loss, via a radiation pressure driven wind, maintains a low temperature photosphere for several months or years (Geisel et al. 1970; Bath 1978; Ney and Hatfield 1978). Because the radius at which the pseudo-photosphere is formed determines the "effective" temperature of the layers, at luminosities of $10^4 L_\odot$, photospheric radii of $10^{12}$ cm will produce continuum energy distributions characteristic of F (or later) supergiants. That is exactly what is observed for novae.

Ultraviolet data have now been obtained for more than a dozen novae with the IUE satellite. The data obtained late in the outburst have been analyzed and published for many of them (Starrfield and Snijders 1987; Starrfield 1988) while the spectra obtained near maximum optical light have never been analyzed and are seldom shown. Nevertheless, these data are an important source of information about the expanding layers at the beginning of the explosion and now that the techniques have been developed to analyze these data we expect to see this situation change rapidly.

2. Physical Model and Assumptions

In order to proceed with the analysis, some of us have developed a program to calculate model stellar atmospheres (Shaviv, Wehrse, and Wagoner 1984; Spies et al. 1987). These models are calculated with the following assumptions: 1) spherical symmetry (not plane parallel), 2) the density follows a power law with an exponent around 2 or 3 (in contrast to the supernova models that have a density exponent approaching 7 to 10), 3) LTE (including scattering), 4) radiative equilibrium, and 5) the expansion velocity is proportional to the radius. All of the relevant opacity sources are included so that we will be able to calculate the effects of the iron forest (cf., Baschek and Johansson 1986) and then determine the expansion opacity (Karp et al. 1977).

The original motivation for the development of this code was to analyze the spectra of SN II and to try
Figure 2b. The LWP image of Nova Vul 1984 #1 taken just after the spectrum shown in Figure 2a. Note that each spectrum is scaled to the strengths of the emission lines in the given spectral region.

Figure 1. Comparison of a theoretical energy distribution for a line-blanketed, spherical, expanding model atmosphere with the appropriate black-body energy distribution. This model had $T_e = 10,000$ K and $E(B-V) = 0.3$. The outer radius was $10^{12}$ cm and the density exponent was 2.

Figure 2a. The SWP image of Nova Vul 1984 #1 taken about 15 days after discovery. This slow nova was still at maximum light. The cool continuum is obvious and this spectrum looks completely unlike spectra obtained later in the outburst. Lyα is present and so strong that the other lines would not have been visible.
and understand the cause of the large ultraviolet opacity in these objects. In fact, it has been shown that the code can be applied to this problem with excellent agreement between theory and observations (Spies et al. 1987).

In Figure 1 we show the results of the initial attempt to calculate a model for a nova atmosphere near maximum. The model atmosphere had a radius of \(10^{12}\)cm, a density law exponent of 2, an effective temperature of 10,000\(K\), \(E(B-V)=0.5\), and included 30,000 lines. The upper line is the equivalent black body curve and shows the large amount of ultraviolet opacity present in this model. It is important to note that even with the large number of blends, there are only a few lines apparent in the spectrum and in order to analyze a nova we will have to do spectral line synthesis.

We are also in the process of developing a method to facilitate our line identifications for nova spectra using a technique similar to that outlined for normal nova spectra by Branch (1987). We use the Saha and Boltzmann equations and the line list of Kurucz and Petrymann (1975) to compute the strongest expected lines in each wavelength interval.

3. IUE Observations of Novae

We have obtained early spectra of numerous nova and in this section we show a few representative LWP and SWP spectra. Figure 2a and 2b shows spectra of Nova Vul 1984 #1 taken on day 245 of 1984 when the nova was at 7.0m; Figure 3a and 3b shows spectra of Nova Vul 1984 #2 taken on day 1 of 1985 when this nova was at 6.5m. Finally, in Figure 4a and 4b we show spectra of Nova And 1986 obtained on day 343 of 1986 when this nova was at 8.8m. This series of spectra emphasize our statements about the structure of the atmosphere at maximum optical light. The cool continuum is obvious and the strongest features are probably caused by Si I and Fe I. Many of the other emission lines are probably blends of lines from elements such as iron, nitrogen, carbon, oxygen, and silicon. Unfortunately, these spectra are too complex for proper line identification and we have also obtained some high dispersion spectra in order to improve our wavelengths (see Sion et al. 1987). In fact, as can be seen from Figure 1, it is likely that most of the lines that we see are blends.

We also note that there is a general similarity of the early ultraviolet nova spectra with those of SN 1987A obtained on the first day of its outburst. Of course, the lines are much broader in SN1987A and it is much harder to identify the elements leading to the specific blends. In fact, we should not be surprised at the resemblance since we are examining material with a great deal of hydrogen and helium. One motivating factor in this study is to apply the codes designed for studying the supernova to a study of the nova since there is so much more data on novae. In addition, once we have identified the features in the nova spectra, it will then be possible to take the nova spectra, broaden them, use this data to assist in the analysis of the SN spectra, and ultimately determine which elements are contributing to the broad blends in SN1987A.

4. Summary and Discussion

We have begun an analysis of the early spectra of novae in an attempt to develop a completely new method (as applied to novae) to determine the elemental abundances in these exciting objects. We shall use a new stellar atmosphere code that includes the effects of sphericity, expansion, and numerous lines to calculate model atmospheres for novae at maximum. This same code is being used on comparable studies of SN 1987A.

This will allow us to determine the abundances for novae in a completely independent way from the commonly used nebular studies of the emission lines seen much later in the outburst when the density has dropped to where photoionization and recombinations are the only important factors effecting the line strengths.

This study would not have been possible without the rapid response of the IUE Observatory to our requests for Target-of-Opportunity observations of novae and we are grateful to the IUE observatory for their continued support of nova observations. The data were reduced with the facilities of the RDAF at the University of Colorado which are supported by NASA Grant NAS5-28731 and T. Armitage's help is gratefully acknowledged. We also acknowledge partial support for this research from NASA, NSF, and the DOE through grants to our various institutions.

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Figure 3a. The SWP image of Nova Vul 1984 #2 obtained on January 1, 1985 just a few days after discovery. Most of the same lines are present as in Nova Vul 1984 #1 but the relative strengths differ. This may be caused by either a real abundance difference or because of differences in the atmospheric conditions.

Figure 3b. The LWP image of Nova Vul 1984 #2 obtained at the same time as the SWP image in Figure 3a. Note the strong P Cygni profile of Mg II 2800Å. Note the difference in scaling from Figure 3a to 3b.

Figure 4a. The SWP image of Nova Andromeda 1986 obtained in December 1986 about 5 days after discovery. Again, note the striking similarity in the lines present in all three SWP spectra.

Figure 4b. The LWP image of Nova Andromeda 1986 obtained just after the SWP image. In this spectrum it appears that Mg II 2800Å is completely in absorption. In fact, Mg II was never very strong in this nova. Note the difference in scaling from Figure 4a to 4b.
Coordinated spectroscopic observations of Nova Muscae 1983 (=GQ Mus) were carried out during its nebular stage in the UV and optical spectral range. The observations were carried out during the period 1984 to 1987 using the facilities of the Villafranca Satellite Tracking Station, the European Southern Observatory on Cerro Sa Silla, and the Cerro Tololo Inter-American Observatory. The combination of the data from the UV and optical spectral ranges allows to determine physical parameters like electron densities, temperatures and chemical composition in the ejecta, mass of the ejecta, and the interstellar extinction towards the nova. A pronounced overabundance of He, C, N, and O has been found (Krautter and Williams, 1988a).

The spectroscopic observations show a steady increase in ionization with time in the ejected envelope. Coronal lines like [FeIX] 6374 and [FeXIV] 5303 are of considerable strength in 1987. The ionization is probably due to photoionization from a hot radiation source, whose temperature increases with time. More details will be found in Krautter and Williams (1988b). The observations can be understood in the context of the thermonuclear runaway model of the outburst of a classical nova.
THE 1981 OUTBURST OF THE OLD NOVA GK PERSEI

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ABSTRACT

GK Per was observed in 1981 with the IUE, during its rise, maximum, and subsequent return to minimum. In outburst, GK Per is luminous but much redder than dwarf novae or standard model accretion disks. The observed spectrum can be explained qualitatively with the Ghosh and Lamb model for the interaction of an accretion disk with the magnetic field of the accreting white dwarf. N V and He II are enhanced relative to other emission lines during outburst. This can be understood with photoionization by very soft X-rays having a luminosity comparable to that of the hard X-rays.

Keywords: Cataclysmic Variables, Old Nova, Dwarf Nova, Intermediate Polar, Ultraviolet

1. INTRODUCTION

GK Per is an old nova which continues to have dwarf nova-like outbursts of 2.5-3.0 magnitudes since reaching minimum after the 1901 nova event. These outbursts occur irregularly every few years and each last a few months. In early 1981 it underwent such an outburst. The distance to GK Per is well established at 470 pc (Ref. 6) from the observed expansion of the nova shell. It is a double-lined spectroscopic binary (Ref. 7 and references therein) with a period of 1.996803 days, a mass ratio of 3.610.5, inclination of -73 degrees. The white dwarf primary has a mass of 0.9±0.2 M\(\odot\) with a rotation period of 351.34s as measured by EXOSAT. The secondary is a KO IV star of 0.2 M\(\odot\). GK Per has been suggested as an intermediate polar.

Here we report the IUE observations of the outburst which occurred in early 1981, and optical and infrared photometry before and after the outburst. Photographic spectra of this same outburst have been described in Ref. 1. More detailed discussion on the data, results and interpretations is given in Ref. 12.

2. RESULTS

Figure 1 shows the observed IUE spectra of GK Per. The continuum is dominated by the strong 2200 A interstellar absorption feature. Dereddening procedure using the extinction curve of Savage and Mathis (Ref. 8) yields an E(B-V)=0.3 which is three times higher than that deduced by McLaughlin (Ref. 6). After correcting for the reddening and assuming the secondary star contributes about 1/3 of the blue light, we estimate that the outbursting component brightened by a factor of 60 in the UV and a factor of 20 at V. With the known distance, we further estimate that the system has L = 20 L\(\odot\) at maximum (adopting a bolometric correction of a B8 star) and L = 2.3 L\(\odot\) at minimum (combined UV optical and IR data) with a third of the luminosity at minimum coming from the secondary star. The dereddened flux distribution at different outburst stages is shown in Figure 2. In the 1200-3300 A region, GK Per is much redder than dwarf novae and novalike variables (e.g. Refs. 11, 9) during outburst. It is also impossible to fit GK Per with the standard, optically thick accretion disk models (e.g. Ref. 4).

The following emission lines are definitely present in GK Per: N V \(\lambda\)1240, Si IV \(\lambda\)400, C IV \(\lambda\)1550, He II \(\lambda\)1640, and Mg II \(\lambda\)2800. N IV \(\lambda\)1486 is probably present in some spectra and the strong feature at 3133 A which is present only in the spectrum when GK Per was at maximum is tentatively identified as originated from O III. During outburst N V and He II lines are enhanced relative to C IV, and Mg II seems to have decreased relative strength.

3. DISCUSSION

GK Per is relatively luminous both at minimum and maximum states, yet its intrinsic flux distribution is much redder than any of the dwarf novae. The observed 351-second X-ray pulsations (Ref. 10) and the related optical modulation (Ref. 5) suggest that GK Per is an intermediate polar, a system whose white dwarf has a strong enough magnetic field to disrupt the inner accretion disk, but not the outer disk. Ghosh and Lamb (Ref. 3) predict that the disruption of the accretion disk by the interaction with the stellar magnetic field leads to the modification of disk temperature.
distribution. The calculations of Ghosh and Lamb estimate the degree of penetration of the stellar magnetic field in the accretion disk outside the very narrow boundary layer in which the disk is disrupted, and they find that the field dominates the transport of angular momentum in a very large transition zone. The field modifies the temperature distribution in this zone such that the temperature is lower inside the corotation radius than predicted by a standard accretion disk model, and higher outside. The cooler temperatures at small radii prevent the disk from being too blue, and the hotter outer regions provide the necessary luminosity with a smaller accretion rate. The model based on the Ghosh and Lamb predictions fit the spectrum and luminosity of GK Per with an inner radius and accretion rate about 20 times smaller than the model based on a standard disk with its center removed.

Figure 1. Observed IUE spectra of GK Per: a) during rise to maximum, b) at maximum, c) after return to minimum

Figure 2. The dereddened continuum flux distribution of GK Per during the outburst of early 1981. The filled circles show the flux distribution during the rising and maximum states, the plus symbols show the flux distribution during the decline from maximum. The solid lines show the flux distributions of the three models discussed in Wu et al. 1988. The dashed lines are not estimates of flux but serve only to connect the flux at V to that at the long wavelength end of LWR.
X-ray emission in the 0.2-4 keV range was observed from GK Per at minimum (Ref. 2) and that in the 2-20 keV range was observed during maximum (Ref. 10). The observed luminosities can be reconciled within factors of two of those expected from the accretion rates derived from the UV and optical emission in an intermediate polar model. The He II intensities and enhancement during outburst are compatible with a soft X-ray luminosity equal to the observed hard X-ray luminosity. Furthermore, it is plausible that the increase in soft X-ray luminosity during outburst is accomplished by increasing the temperature of the heated portion of the white dwarf surface. Consequently carbon is mostly ionized to C V leading to the increased N V / C IV ratio observed during outburst.

4. REFERENCES

OBSERVATIONS OF CLASSICAL NOVAE IN OUTBURST

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ABSTRACT

Over the past 10 years the IUE Satellite has obtained ultraviolet data on a number of novae in outburst and the characteristics of every one of the outbursts have been different. In addition, our group has also obtained optical and infrared data on many of the same novae. In this paper we present the data on three members of the carbon-oxygen class of novae.

1. Introduction

We are continuing to obtain data on novae in outburst and the novae that are still bright enough to study with the IUE Satellite are Nova Vul 1984 #2, Nova And 1986, Nova Vul 1987, and Nova LMC 1988. Nova Vul 1984 #2 is a slow oxygen-neon-magnesium nova, Nova And is a moderately fast carbon-oxygen nova, and Nova Vul 1987 had a period of about a month with nearly constant light and then started a slow decline but it exhibited a very deep transition phase when it formed dust.

The ultraviolet observations of novae done with the IUE Satellite have proved to be of extreme importance in understanding the cause and evolution of the outburst. As summarized in reviews by Starrfield and Snijders (1987), Starrfield (1987), and Starrfield (1988), the ultraviolet spectra have shown that there are at least two classes of recurrent novae, and have allowed much more accurate determinations of elemental abundances. The importance of the IUE data is that there are spectral lines in the 1200Å to 3300Å wavelength range that come from elements which do not have analyzable (or any) lines in the optical. These lines can be used to determine elemental abundances, expansion velocities, and the amount of mass ejected. Many of these lines are the commonly observed and well understood medium ionization UV resonance and intercombination lines observed in most emission line objects. However, their time-dependent behavior in novae can be used to constrain the abundances that are determined for the ejected material. A table of such lines and the time variations of their fluxes for one nova can be found in Williams, et al. (1985).

Because of IUE data, we have recently been able to identify a new class of novae (Starrfield, Sparks, and Truran 1986). Finally, continuum flux distributions can be used to determine temperatures of the white dwarf and/or mass transfer rates onto the white dwarf.

In companion papers in this meeting we discuss the ultraviolet observations of Nova Vul 1984 #2, a slow oxygen-neon-magnesium nova, the ultraviolet observations of Nova V394 CrA a very fast recurrent nova, and two recent novae: Nova Vul 1987 and the 1988 nova in the LMC. In this paper we present and discuss the ultraviolet data on 3 of the other novae that we have observed in the last two years. These are Nova Vul 1984 #1, Nova And 1986, and Nova Her 1987. They are all apparently carbon-oxygen novae with differing ejection velocities and rates of decline.

2. Observations

Nova PW Vul 1984 #1. The first slow nova to be studied by IUE was PW Vul (1984 No. 1). We were able to obtain spectra for this nova from maximum light in August 1984 until late in 1986. Optical and IR data for this nova were presented by Kenyon and Wade (1986) who determined a distance of 1.2 kpc. They also report He/H of 0.13 (by number) and that oxygen was enhanced in the ejecta. They did not find a neon enhancement. The IUE data are currently being
reduced and analyzed. Spectra taken on May 24, 1985 (SWP 26244 and LWP 6264) and October 29, 1985 (SWP 26997) are presented in Figures 1 and 2. The LWP spectrum taken in October 1985 was underexposed. Note that from May to October the peak SWP fluxes fell by almost a factor of 10. The strongest lines are from CIV, OIV, NIV, NIII, CIII, and NV. This is obviously a carbon oxygen outburst since none of the strong neon or magnesium lines, found in Nova Vul 1984 #2 (Starrfield et al., 1988; these proceedings), are present in these spectra. The nitrogen came from carbon and oxygen by means of hot hydrogen burning in carbo-oxygen enriched material.

Nova Andromeda 1986 was discovered in outburst in early December 1986 and we began obtaining spectra almost immediately. We have been able to follow it through its outburst and are also obtaining optical data. Spectra taken at maximum are shown in a paper by Smykcer et al. (1988; these proceedings). In Figures 3 and 4 we display SWP and LWP spectra obtained on July 12, 1987 and a SWP spectrum obtained on November 15, 1987. This last spectrum took 105 minutes and we were unable to obtain an LWP spectrum. This is a moderately fast nova; the peak flux of CIV 1549Å fell by less than a factor of two in the 4 month interval. The spectral features shown in these two spectra are quite similar to those of Nova Vul 1984 #1 and it must also be a carbon-oxygen nova.

Nova Hercules 1987 was discovered in outburst early in 1987 and we decided not to observe it since we were already following two other novae (Nova Vul 1984 #2 and Nova And 1986) and the European team was observing Nova Cen 1986. In April 1987 Gehrz and Jones (IAU Announcement Card #4371) found that it had formed dust with a temperature of about 1000K. In addition, they noted that there was evidence for strong [Ne II] emission at 12.8μm. Then in May 1987, Andrillat (IAU Announcement Card #4388) reported that she had found it to be in the nebular stage with strong [O III] and NIII lines present in the spectrum.

In addition, she also reported that [Ne III] 3684Å and [Ne V] 3464Å and 3426Å were present in the spectrum. These two reports suggested that this could be another oxygen-neon-magnesium nova and given this possibility, we obtained an SWP and LWP spectrum on June 11, 1987. These spectra are shown in Figure 5. As in the two other novae discussed in this paper, the spectra show mostly lines from carbon, oxygen, and nitrogen ions and it appears to be a carbon-oxygen nova. The strongest lines are from C IV, C III, N III, N V, CII, O IV, and O III. Given this result, we obtained no further spectra of this nova.

3. Summary

We have obtained ultraviolet spectra for three novae that appear to have ejected material rich in oxygen, nitrogen, and carbon. We will be unable to determine if these elements are actually enhanced in the ejecta until we have finished our nebular analysis. This work is in progress.

Acknowledgements

This study would not have been possible without the response of the IUE Observatory to the request for continuing observations of novae in outburst and we are grateful for their continued support of this study. The data were reduced with the facilities of the RDAF at the University of Colorado, which are supported by NASA Grant NASS-28731, and the assistance of T. Armitage. We also acknowledge partial support for this research from NASA, NSF, and the DOE through grants to our various institutions.

References


Figure 1a. This SWP spectrum was a 20 minute exposure of Nova Vul 1984 #1 obtained on May 24, 1985. The strong lines are from carbon, nitrogen, and oxygen.

Figure 1b. This 10 minute LWP spectrum of Nova Vul 1984 #1 was obtained on May 24, 1985. Note that even after nearly a year in outburst there is still a continuum present.
Figure 2. This 15 minute SWP spectrum of Nova Vul 1984 #1 was obtained on October 29, 1985. The peak fluxes have declined considerably.

Figure 4a. This 30 minute SWP spectrum was obtained of Nova And 1986 on July 12, 1987. Note that the strong lines are from carbon, nitrogen, and oxygen ions.

Figure 3a. This 30 minute SWP spectrum of Nova Her 1987 was obtained on June 11, 1987. There are apparently no lines of neon or magnesium present.

Figure 4b. This 45 minute LWP spectrum of Nova And 1986 was obtained on July 12, 1987.

Figure 3b. This 65 minute LWP spectrum was obtained of Nova Her 1987 on June 11, 1987. Not only is there a red continuum present but the neon lines seen by Andrillat in the optical are visible at the red end of the spectrum.

Figure 5. This 105 minute SWP spectrum of Nova And 1986 was obtained on November 15, 1987 nearly a year after maximum.
ABSTRACT
Nova Vul 1984 #2 has been observed with the IUE Satellite from December 1984 through November 1987 and we expect to be able to observe it with the IUE Satellite for at least another two years. These spectra are characterized by strong lines from Mg, Ne, C, Si, O, N, and other elements. Data obtained in the ultraviolet, infrared, and optical show that this nova is ejecting material rich in oxygen, neon, and magnesium.

1. Introduction
Nova occur in cataclysmic binary systems in which a Roche lobe filling secondary is losing hydrogen-rich material through the inner Lagrangian lobe onto a white dwarf primary. Theoretical studies show that the accumulating shell of hydrogen on the white dwarf is unstable to a thermonuclear runaway and simulations of this phenomena reproduce many of the observed features of a nova explosion (Starrfield, Truran, and Sparks 1978; Sparks, Starrfield, and Truran 1978; Gallagher and Starrfield 1978; Starrfield, Sparks, and Truran 1985, 1986; Starrfield, Sparks, and Shaviv 1987). The models further imply that the energetics of the outburst, and thus the type of nova, is not only sensitive to the abundances of the intermediate mass elements, but also depends on other factors such as the mass of the accreted shell, while dwarf mass, and accretion rate (Truran 1982; Starrfield 1986, 1987; Shaviv and Starrfield 1987).

In addition, as a direct result of IUE observations of previous novae such as V603 CrA (Williams et al. 1985) and V1370 Aql (Snijders et al. 1987), we were able to show that there were two classes of novae: those in which the outburst occurs on a carbon-oxygen white dwarf and those in which the outburst occurs on an oxygen-neon-magnesium white dwarf (Starrfield, Sparks, and Truran 1986).

The third nova to show the characteristics of an oxygen-neon-magnesium white dwarf was Nova Vul 1984 #2. However, unlike the previous novae, it is a slow nova that has declined from a maximum visual magnitude of +5 to +12 in the last 3.5 years. This has allowed us to follow its outburst both in the optical and in the ultraviolet.

In addition, X-ray data were obtained early in the outburst with Exosat which indicated that as early as 1985 there was a hot source in the system radiating at a temperature of about $3 \times 10^{35}$K. This high temperature is fully expected by the numerical modeling (Starrfield, Sparks, and Truran 1986) and was observationally confirmed by infrared observations of coronal lines (Greenhouse et al. 1987). In addition, other infrared studies found that this nova formed silicate dust, which implies an overabundance of oxygen with respect to carbon (Gehrz et al. 1986), and showed strong infrared evidence for enhanced neon (Gehrz et al. 1986). All of these data warrant continued observations of this nova.
We are also continuing to model this outburst in order to learn more about outbursts that occur on oxygen, neon, and magnesium white dwarfs. Further work on this nova is required since our published studies of outbursts on oxygen, neon, and magnesium white dwarfs only produced "fast" outbursts (Starrfield, Sparks, and Truran 1986). We are currently improving our hydrodynamic stellar evolution code in order to calculate new models of this nova. In particular, improvements include the effects of accretion energy on the evolution, elemental diffusion between the accreted material and the white dwarf, and a large nuclear reaction network with new rates.

2. Observations of the Outburst

In Figures 1, 2, and 3, we show SWP and LWP images of Nova Vul 1984 #2 on June 24, 1983 (the LWP image was obtained on July 2, 1985; September 11, 1986; and November 15, 1987. These spectra are not the only ones that we have obtained but were chosen to represent the changes that have occurred in this object over time. The spectrum shown in Figure 1 was taken just after the nebular lines began to appear and the spectrum shown in Figure 3 is the latest spectrum that we have obtained. Table 1 gives the lines, their identification, when known, and whether or not they were present on a given date.

It is clear from the lines that are present that this is a "neon" nova. It has virtually the same elements and ions as found in both Nova V693 CrA (Williams et al. 1985) and Nova V1370 Aql (Snijders et al. 1987). The primary indicators are the strength and simultaneous presence of [NeII] 1602Å and [NeIV] 2422Å. We also note that [NeV] 3346Å, is one of the strongest lines in the spectrum. Note that at the same time as these spectra were taken, Gehrz et al. (1986) reported that [NII] 12.8mm was strong. The great strength of these multiple ionization states of neon, all occurring at the same time, strongly argue for its enhancement in this nova. The strength of the magnesium and oxygen lines also argues that these elements are overabundant. All of the fluxes have been determined over time. The spectrum shown in Figure 3 is the latest spectrum that we have obtained.

In addition to the ultraviolet data, we have also obtained infrared and optical data on this nova. The infrared data has been discussed and reviewed by Gehrz (1988). The data show that this nova formed silicate grains and is currently exhibiting coronal line emission. In Figures 4 and 5, we show optical spectra obtained by one of us (RMW) at the 1.8m Perkins Reflector of the Ohio Wesleyan and Ohio State Universities at the Lowell Observatory. The spectra are numbered from the beginning of the outburst. Note the strong emission from [Ne III] which is still present even very late in the outburst. There are also coronal lines present in the optical spectra.

3. Discussion

As already mentioned in Starrfield, Sparks, and Truran (1986), the presence of an oxygen, magnesium, neon white dwarf in a close binary system is an important constraint on our theories of stellar evolution. First, the calculations of single star evolution show that in order for a star to survive carbon burning its mass on the main sequence must exceed about $8M_{\odot}$ to $10M_{\odot}$.

Second, for it to end up as a member of a nova system requires that it had to evolve as a single star for much of its life before its radius reached to the point where it interacted with the secondary. At this point, it had to have lost most of its main sequence mass (if it had not lost it already) which carried away most of the angular momentum of the binary. Because it was in a binary, it lost all of the remaining hydrogen and helium layers and, possibly, some of the carbon burning layer. However, the differences in the ejected carbon abundances of V693 CrA, V1370 Aql, and V1500 Cyg suggest that the amount of carbon lost is variable. On the other hand, hot hydrogen burning will produce a significant amount of carbon from oxygen.

Acknowledgements

This study would not have been possible without the rapid response of the IUE Observatory to the request for Target-of-Opportunity observations and we are grateful for their continued support of nova observations. The data were reduced with the facilities of the RDAF at the University of Colorado, which are supported by NASA Grant NAS5-28731, and the assistance of T. Armitage. We also acknowledge partial support for this research from NASA, NSF, and the DOE through grants to our various institutions.

References


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Figure 1a. The SWP spectrum was obtained on June 24, 1985 at a time when the magnitude of the nova was +10. It is a 24 minute exposure. Lyα was present at all times but is too strong to show on the same plot. Note that the flux scaling is different in all of the plots.

Figure 1b. The LWP spectrum was obtained on July 2, 1985 and is a 4 minute exposure. Note that six months after discovery this slow nova still shows a cool continuum. The strong line at 3346Å is either [Ne V] or [Ne III]. Mg II 2800Å is very overexposed.

Figure 2a. The SWP spectrum was obtained on September 11, 1986. The nova had declined to 11.4 and this was a 38 minute exposure. The strong line at 1602Å is [Ne IV].

Figure 2b. The LWP spectrum is a 12 minute exposure on the same day as the SWP spectrum. By this time [Ne IV] 2422 is present and strong and the line at 3346Å is definitely [Ne V]. The simultaneous presence of [Ne IV] 1602Å and 2422Å requires that neon be enhanced. Again Mg II 2800Å is very exposed.
Figure 3a. The SWP spectrum is a 200 minute exposure and the nova has now declined to 13.4. It was obtained on November 15, 1987. [Ne IV] 1602Å has declined markedly since the last SWP spectrum was taken.

Figure 3b. The LWP spectrum was taken on the same day as the SWP spectrum and is a 40 minute exposure. While the neon lines are still prominent, Mg II 2800Å has virtually disappeared.

Figure 4. This is a montage of the optical spectra taken by R.M. Wagner. The number on the RHS of each spectrum is the day since outburst. Note how slowly this nova became nebular. The great strength of the neon lines, with respect to the [O III] lines, also argues for non-solar neon abundances.

Figure 5. This is the latest optical spectrum of the nova obtained by Wagner. The [Ne IV] lines are still present and strong enough to use to determine the density and temperature in the region where [O III] is formed (see text).
OBSERVATIONS AND SIMULATIONS OF RECURRENT NOVAE: U SCo AND V394 CRA

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ABSTRACT

We present observations and analysis of the August 1987 outburst of the recurrent nova V394 CrA. This nova was extremely fast and its outburst characteristics closely resembled those of the Recurrent Nova U SCo. In addition to the observations, we have performed hydrodynamic simulations of the outbursts of recurrent novae and present a summary of these results as applied to the outbursts of V394 CrA and U SCo.

1. INTRODUCTION

The IUE Satellite has observed four recurrent novae during its 10 year lifetime. These are WZ Sge, U SCo, RS Oph and V394 CrA. The ultraviolet data showed that WZ Sge was a long period dwarf nova and, therefore, its outburst is not relevant to this work which is concerned only with recurrent classical novae. The 1979 outburst of U SCo was well studied both in the ultraviolet, with the IUE Satellite, and in the optical (Williams et al. 1981). The May 1987 outburst was well studied in the optical (Sekiguchi et al. 1987) but the nova was too close to the sun to be studied with the IUE Satellite. Recently, some of us have published simulations of its 1979 outburst (Starrfield, Sparks, and Truran 1985).

RS Oph is more of a puzzle and its outburst resembles that of a nova exploding into a stellar wind. In addition, there is some controversy about what caused its outburst. A summary of its behavior can be found in the proceedings of a symposium held specifically to discuss its outburst and that of other recurrent novae (Bode 1986).

V394 CrA exploded in August 1987 and we were able to obtain both optical and ultraviolet data. A previously recorded outburst occurred in 1949 (Duerbeck 1987). These data are now being analyzed and this nova appears to have had an outburst similar to that of U SCo. The data from this outburst will be presented and discussed in this paper. In a companion study, we have done new simulations for the outbursts of both U SCo and V 394 CrA. We assumed a 1.35M_☉ hot white dwarf accreting at high rates. Given mass accretion rates as high as 10⁻⁶M_☉ yr⁻¹, it is possible to achieve a runaway in less than 3 years from the beginning of accretion. These calculations have been done with new boundary conditions that include the effects of the accretion energy on the thermonuclear runaway. They also include the effects of radiation pressure driven mass loss.

2. The 1987 Outburst of V394 CrA

V394 Coronae Australis was reported to be in outburst by Lilley (IAU Circular 4428) who also noted that spectra taken on August 3, 21, 1987 showed intense He emission blended with [NeII] plus a weak continuum. McNaught (IAU Circular 4429) noted the coincidence in position of V394 CrA with a star of mag -18 on a UK Schmidt J Plate at a position of α = 17h 56m 58.18s, δ = -39° 00' 29.3". Some of us began obtaining spectra with the CTIO 1-meter telescope on August 4, 1987 and reported that the nova (IAU Circular 4430) showed broad emission from the Balmer lines, He I, and He II. A spectrum obtained on August 4, 1987 is shown in Figure 1a and a spectrum obtained on August 19, 1987 is given in Figure 1b. Note the rapid evolution and decay of the emission lines over the two week interval. Exactly the same behavior was found for U SCo (Barlow et al. 1981). Note also that at all times He II 4686Å is stronger than HeI. This inversion of line strengths is unusual but also seen in U SCo and some of the other old novae. However, we also note that V1500 Cygni 1975, which also shows He II 4686Å stronger than HeI has been found to be an AM Her variable (Schmidt, Stockman, and Lamb 1988, preprint).

Unfortunately, we were unable to obtain an IUE spectrum.
Figure 1a. The optical spectrum of V394 CrA obtained on August 4, 1987. The line identifications for the strongest lines can be found in Table 1. Note the strength of HeII 4686Å as compared to Hβ. The structure in Hα is certainly real and characteristic of novae ejecta.

Figure 1b. The optical spectrum on August 19, 1987. The nova declined very rapidly over the two week period. This behavior is analogous to that of U Sco. However, the 4640Å complex was much stronger in U Sco than in this nova.
until August 23, 1987 and by then the nova had faded considerably. We show this spectrum as Figure 2a and 2b. We give the entire usable spectrum in Figure 2a in order to demonstrate the excellent match to a spectrum that we obtained of the Recurrent Nova U Sco on June 30, 1979 (Williams et al. 1981). In Figure 2b, we show only the region from 1300Å to 1950Å in order to show the profiles of CIV 1550Å and NIII 1750Å in more detail. Note that the same blend at 1750Å appears in the June 30, 1979 spectrum of U Sco. We do not have an identification for the line at 1735Å. The most important features to notice about this spectrum is the great strength of the nitrogen lines. Their strength strongly supports the suggestion of Heathcote, Gomez, and Williams (IAU Announcement Card 34430) that nitrogen is enhanced in this nova.

3. Discussion

The strong resemblance of both the optical and ultraviolet spectra of V394 CrA to those obtained of U Sco during its 1979 and 1987 outbursts (Barlow et al. 1981; Williams et al., 1981; Sekiguchi et al., 1987) strongly suggests that these objects are closely related. A high priority of future optical observations should be a study of both recurrent novae at minimum in order to determine the parameters of the binary systems.

The current hydrodynamic modeling of recurrent novae (see Starrfield, Sparks, and Shaviv 1988, and references therein) implies that we are witnessing the effects of thermonuclear runaways on very massive white dwarfs. This conjecture can be tested by radial velocity studies of these two systems at minimum. In fact, their outbursts are so rapid that they have already returned to minimum but are not too faint to be studied with large telescopes in the southern hemisphere.

The theoretical studies of these systems also show that it is possible to obtain a thermonuclear runaway and mass ejection even if the secondary is transferring material with no CNO enhancement. The luminosity of the shell source is sufficient to drive mass from off of the white dwarf purely by radiation pressure. However, only a small fraction of the accreted mass is ejected during the outburst; most of it is burnt to helium during the runaway and acts purely to increase the mass of the white dwarf toward the Chandrasekhar limit. Therefore, we predict that these two systems, U Sco and V 394 CrA, are evolving to a point where the white dwarf will exceed a mass of 1.4M⊙ and become a neutron star. These systems will then become low mass X-ray binaries. An argument in favor of this suggestion is that the low mass X-ray binaries seem to be transferring material rich in helium (Williams 1988, in preparation).

Acknowledgements

This study would not have been possible without the rapid response of the IUE Observatory to the request for Target-of-Opportunity observations of V394 CrA. We are grateful for their continued support of nova observations. The data were reduced with the facilities of the RDAF at the University of Colorado which are supported by NASA Grant NAS5-28731 and we are grateful for the excellent assistance from T. Armitage of that facility. We also acknowledge partial support for this research from NASA, NSF, and the DOE through grants to our various institutions.

References


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Figure 2a and b. The IUE spectrum of V394 CrA obtained on August 23, 1987. The upper plot shows the entire usable spectrum while the lower plot emphasizes the strong lines and shows the peculiar profile around NIII] 1750Å. This spectrum closely resembles that of U Sco obtained on June 30, 1979.
ABSTRACT

We present a brief summary of the outburst for a nova that was discovered in November 1987 and has been followed since that time. Although we were able to observe it with the IUE at maximum, its ultraviolet energy faded rapidly and after the first two weeks we were no longer able to observe it at IUE wavelengths. It was observed to form a thick dust shell and currently is in the nebular stage.

1. Introduction

This currently bright nova was first detected in outburst on November 15, 1987 (UT: IAU Announcement Card #4488). The position of the nova was found to be at $\alpha = 19^h 02^m 32.5$ and $\delta = +21^\circ 41' 39"$ (1950.0). These co-ordinates were determined by Gehrz (IAU Announcement Card #4501). By coincidence, one of us (S. S.) was at the IUE Observatory to obtain ultraviolet data on bright novae. We obtained a very underexposed LWP spectrum at this time and about one week later we obtained two sets of slightly underexposed SWP and LWP spectra two nights apart. After analysis, we found that the ultraviolet energy had decreased by nearly a factor of 2 between these two nights. This rate of decline is unprecedented when compared to the other novae that have been observed in the early stages of their outburst. In fact, the rapid rate of decline in the ultraviolet was more like that of SN1987A than that of a typical "fast" nova. Over the same time period, we also obtained optical and infrared data. Gehrz did not detect the nova but this was probably caused by the low energy cutoff of the satellite of 2 keV (Dupree 1988, private communication).

2. Ultraviolet and Optical Observations

In this paper we report on our observations of this nova over the first four months of its outburst. The optical data showed major changes in line intensities and line ratios over the first two weeks. As already mentioned, the first attempt to obtain a spectrum of this nova was during the second half of the US 2 shift on November 16, 1987. The exposure times were chosen based on our previous experience with novae at maximum. However, because we were able to observe this nova so soon after discovery, we did try to be conservative and not overexpose the image. To our amazement, there was no detection in the SWP camera and only a faint image was present in the LWP camera. Unfortunately, there was not enough time left in the shift to obtain additional exposures.

We were granted additional time on Monday, November 23, 1987 and Sonneborn obtained the SWP and LWP spectra shown in Figure 1a and 1b. The SWP image is still underexposed after an exposure time of 10 minutes. The LWP image is better but required 2 minutes. Both of these times are long for a nova observed at a visual magnitude, determined from the FES, of about 8.2 m. The appearance of the spectra is not unusual, as compared to other early spectra of novae, although the continuum appears somewhat flatter than those shown in the paper by Stryker et al. (1988; these proceedings).

On November 25, 1987 there was a false report of a supernova in M31. The IUE satellite mobilized to observe it but found no sign of any supernova at the reported location. By that time, it was too late to return the shift to the scheduled astronomer and it was decided to obtain two more exposures of Nova Vul 87. Sonneborn increased the exposure times by a large
factor (SWP: 50min; LWP: 2min 30s) but again found
that the spectra were underexposed. These spectra are
shown in Figure 2a and 2b and a glance at both scales
shows why we were being continuously fooled in
determining an optimum exposure time. The nova had
faded by a factor of 2 in the two nights separating
these two series of images. No previous nova has
faded so fast in the ultraviolet and this rapid decline
is analogous to the behavior of SN 1987A in the first
observations (the supernova declined much more
rapidly, of course).

Almost immediately after the report of the discovery,
Garcia and co-workers at the Whipple Observatory
began obtaining spectra. They found strong P-Cygni
profiles in Hα but all of the other hydrogen lines were
in absorption (IAU Announcement Card #4489). We
(Wade and Starrfield) obtained our first spectrum at
the 2.1-m telescope of the Steward Observatory on the
evening of the 30th of November 1987 and found that
P-Cygni profiles were apparent for some of the strong
lines. This spectrum is shown in Figure 3. In
addition, a continuing series of optical spectra were
obtained by Wagner at the 1.8-m Perkins Reflector of
the Ohio Wesleyan and Ohio State Universities at the
Lowell Observatory (IAU Announcement Card #4501).

One interesting feature of the spectral evolution of
this nova is that the initial Whipple Observatory
spectra showed deep P-Cygni profiles which gradually
disappeared for a short time (Garcia 1987, private
communication). However, they were again obvious by
the time that we obtained the spectrum shown in
Figure 3. Figure 4 shows a spectrum obtained (at the
1.8-m Perkins Reflector by Wagner and Starrfield) in
late December when the P Cygni profiles were again
weak. The appearance, disappearance, and reappearance
of the P-Cygni profiles suggests that more than one
ejection event probably took place. These spectra
also showed lines of Fe II, Mg I, and O I in addition
to the Balmer lines. Andrillat also reported lines of
Cr I, Cr II, He I, and Mg II (IAU Announcement Card
#4511).

At about this time, the nova became too close to the
sun for further observations in the optical. When the
nova reappeared late in January, it was reported to be
fainter than 14th. Our only explanation for this rapid
decrease was that it had formed dust. This hypothesis
was confirmed by the observations of Gehrz with the
2.34-m Wyoming Infrared Telescope on February 24
(IAU Announcement Card #4557) which showed that it
had formed an optically thick dust shell with a
temperature of about 600K.

Wagner obtained another optical spectrum with the
Perkins 1.8-m telescope, on March 13.5 (IAU Announce-
cement Card #4573), and found that it was definitely
nebular. This spectrum is shown in Figure 5. In
Figure 6, we show an early optical spectrum on the
same scale as this last spectrum. The differences are
obvious. The strong lines are due to [O III], [O I], and
[N II]. He reported that the magnitude had continued
to drop and was currently about 17. In addition and
very important, the emission line wavelengths appeared
slightly blueshifted which was consistent with a thick
shell of dust obscuring the redshifted material in the
ejecta.

3. Discussion

Although we continue to claim in our nova Target of
Opportunity proposals that every recent nova outburst
has been unique, we ourselves are still surprised when
a new nova justifies this claim. The rapid decline of
the ultraviolet energy suggests both that it was
somewhat reddened and that a relatively thick shell
was ejected during the outburst. The rapid decline in
the optical, once dust had formed, is analogous to the
behavior of DQ Her during its outburst. In fact, when
the shell was first detected by Gehrz, it was radiating
more energy in the infrared than had been observed at
maximum light in the optical. The dust is probably
carbon dust and this nova most likely ejected material
enhanced in the CNO nuclei. Further analysis of this
outburst is in progress.

Acknowledgements

This study would not have been possible without the
rapid response of the IUE Observatory to the request
for Target-of-Opportunity observations of Nova Vul
1987 and we are grateful for their continued support of
nova observations. The data were reduced with the
facilities of the RAdAP at the University of Colorado,
which are supported by NASA Grant NASS-28731, and
the assistance of T. Armitage. We also acknowledge
partial support for this research from NASA, NSF, and
the DOE through grants to our various institutions.
Figure 2a. This SWP spectrum was obtained on November 25, 1987 and the FES magnitude of the nova was still about 8. This is an exposure of 50 minutes and note that the fluxes have decreased by about a factor of two since the image in Figure 1a.

Figure 2b. This LWP spectrum is a 2.5 minute exposure on the same day as the SWP spectrum in Figure 2a. Note that the fluxes have also decreased between this figure and Figure 1b.

Figure 3. This optical spectrum was obtained on the 2.1-m telescope of Steward Observatory on November 30, 1987.

Figure 4. This spectrum was obtained on December 23, 1987 at the 1.8-m Perkins telescope. The P-Cygni profiles for many of the lines had decreased in strength since the spectrum shown in Figure 3.

Figure 5. This optical spectrum was obtained at the 1.8-m Perkins telescope. The nova had definitely entered the nebular stage and the strongest lines are due to [O III].

Figure 6. This montage shows a comparison of two optical spectra of Nova Vul 87. One was obtained early in the outburst and the other is also shown as Figure 5. Once dust formed in the expanding shell (see text), this nova experienced an extremely rapid decline in its optical magnitude.
ULTRAVIOLET OBSERVATIONS OF LMC NOVA 1988

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ABSTRACT

This currently bright nova was first detected in outburst on March 21, 1988. Its discovery has given us the opportunity of studying the first extragalactic nova in the ultraviolet and we have, therefore, obtained a number of LWP and SWP spectra when it was at maximum. We have also obtained a high dispersion LWP spectrum in order to study the ISM in the Large Magellanic Cloud on a slightly different line-of-sight from that analyzed using SN 1987A.

1. Introduction

Except for a small number of investigations, the studies of novae in external galaxies have been primarily limited to studies of their distribution and light curves. The major studies of the distribution of novae have been done for M31 (Arp 1956; Rosino 1973; Ciardullo et al. 1987). The most recent spectroscopic analyses of novae in M31 have been done by Ciardullo, Ford, and Jacoby (1983) and Cowley and Starrfield (1987).

The spectral features seen in the spectra of the four novae studied by Ciardullo, Ford, and Jacoby (1983) and the one slow nova studied by Cowley and Starrfield (1987) appear quite normal. However, in neither study were the novae followed through to the nebular stage of their evolution (when the density of the expanding shell has fallen to where a large number of forbidden lines from highly ionized species are present) and it is probable, anyway, that they would have been too faint to study when they reached this phase.

We also note that Ciardullo et al. (1987) found that the distribution of bulge novae in M31 follows the light from the bulge and only a few novae appear to come from a disk distribution. However, it seems most likely that most of the novae in the solar neighborhood come from a disk population and we are not detecting the bulge novae in our own galaxy.

The theoretical studies of the nova outburst have shown that the observed properties of the explosion depend upon a variety of factors such as white dwarf mass, white dwarf luminosity, mass accretion rate, and the chemical composition of the mixed (accreted material plus core material) envelope (see Starrfield 1987; Starrfield and Sparks 1987; and Shaviv and Starrfield 1987 for recent reviews). While there is no theoretical reason to expect to find fundamental differences between nova outbursts that occur in different stellar populations, it is still important to study novae in as many different environments as possible and either confirm or deny the theoretical investigations.

While the nearest large galaxy to our own is the LMC and it is known to exhibit nova outbursts with a reasonable frequency (Graham 1987; private communication), there have been no detailed optical or ultraviolet studies of novae in this galaxy. Therefore, when a bright nova was recently discovered in the LMC, we
Figure 1a. This 80 minute SWP spectrum was obtained on March 25, 1988. It is a typical spectrum for a nova near maximum.

Figure 1b. This 30 minute LWP spectrum was also obtained on March 25, 1988. Note the very deep P-Cygni profile for Mg II 2800Å. The deep depression at 3055Å is a camera artifact.

Figure 2a. This is a 160 minute SWP spectrum obtained on March 30, 1988. There are obvious changes over the five day interval.

Figure 2b. This is a 15 minute LWP spectrum obtained on March 30, 1988. The flux scaling between this spectrum and Figure 1b are identical in order to emphasize the real changes that have occurred in the spectrum over the 5 day interval.
decided to observe it both optically and with the IUE satellite. In addition, this nova turned out to be bright enough, in the wavelength range of the LWP camera, to enable us to obtain a high dispersion spectrogram by combining US1 and Vilspa shifts. Aside from the basic interest in a high dispersion study of novae (Sion et al. 1986), this image will allow us to sample the ISM in the LMC on a slightly different line of sight than was analyzed for SN1987A. It might be possible to determine which, if any, of the species found in the SN1987A analysis (Dupree et al. 1987) actually came from the circumstellar material surrounding the progenitor and not the general ISM.

2. Observations

This nova was discovered by Garradd on March 21.484 1988 UT (IAU Announcement Card #4568). A precise position of $\alpha = 5^h 36^m 01.925$ and $\delta = -70^\circ 23' 15.2''$ (1950.0) was provided by McNaught (IAU Announcement Card #4569). We began obtaining optical spectra at the 1.5-m telescope at the Cerro Tololo Interamerican Observatory and obtained IUE SWP and LWP spectra on March 23, 1988. We were able to obtain more spectra over the next few days and a high dispersion LWP spectrum was obtained on March 30, 1988. These spectra are now undergoing analysis. In this brief report we show only the two best of the SWP and LWP spectra as Figures 1a and 1b and 2a and 2b. The date and exposure times are given in the figure captions. Completely unlike the ultraviolet behavior of Nova Vul 87 (Starrfield et al. 1988; these proceedings), this nova still appears to be getting brighter between the first and last of the spectra. In addition, Mg II 2800Å is becoming stronger with time. We were unable to extract and display the high dispersion spectrum before this meeting. If we are able, we shall present plots of that spectrum during the meeting.

We have recently begun a project to perform spectral syntheses of the early spectra of novae (see Stryker et al. 1988; these proceedings) and these spectra will be among the first that we analyze.

3. Summary

We have obtained the first ultraviolet spectra of a nova in an external galaxy. The spectral features that are seen do not seem unusual for a nova at maximum (see Stryker et al. 1988; these proceedings) but we hope to be able to follow it for a long enough time to be able to study the high ionization lines that appear when the density drops to lower values (the nebular stage). We have also obtained a high dispersion spectrum and will use it to assist in the line identification and to study the line of sight to the LMC about one degree of arc away from SN1987A.

Acknowledgements

This study would not have been possible without the rapid response of the IUE Observatory to our requests for Target-of-Opportunity observations of novae and we are grateful to the IUE observatory for their continued support of nova observations. The data were reduced with the facilities of the RDAF at the University of Colorado which are supported by NASA Grant NAS5-28731 and T. Armitage's help is gratefully acknowledged. We also acknowledge partial support for this research from NASA, NSF, and the DOE through grants to our various institutions.

References

SS CYGNI IN QUIESCENCE

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ABSTRACT

Low resolution spectra of SS Cygni obtained near quiescence show a strong absorption feature near 1225Å. If this feature is interpreted as the red wing of the Lyman-α absorption in the spectrum of the white dwarf component, we find that the star has an effective temperature of 34000±5000K. This information is used to derive limits on the distance. Observations obtained in outburst are used to determine an E(B-V) estimate of 0.04±0.02. While these observations are consistent with the detection of the white dwarf primary on the quiescent scale, they also show that the disk itself can produce Lyman-α absorption resembling that of a white dwarf and that the existence of the feature is not proof that the white dwarf has been detected.

Keywords: cataclysmic variables, white dwarfs, ultraviolet spectroscopy.

1. INTRODUCTION

The capability of IUE to provide medium to high resolution, ultraviolet spectroscopy of sources of tenth magnitude and fainter has resulted in many advances in the study of cataclysmic variables. One example is the apparent identification of the white dwarf primary in the dwarf nova U Gem (Ref. 1). By using IUE’s small entrance aperture Panek and Holm were able to separate the Lyman-α profile of the quiescent source from the solar line scattered by the geocorona. They found that the intrinsic profile of U Gem could be modelled by a 30,000 K, log g = 5 white dwarf atmosphere. In this paper we examine IUE spectroscopy of the dwarf nova SS Cygni in quiescence for evidence of the white dwarf primary that is expected in this system.

2. OBSERVATIONS

We obtained IUE low-resolution spectra of SS Cyg during quiescence [m(FES)=12.08] on 1984 Nov 22 and while approaching quiescence [m(FES)=11.71] on 1984 July 5. These observations included SWP spectra through the small aperture as well as through the large aperture to search for photospheric Lyman-α absorption in the region which usually is contaminated by geocoronal Lyman-α. As seen in Figure 1, both observations show the hot continuum and high excitation emission lines found by Heap et al. (Ref. 2). In addition both show a strong absorption feature in the wavelength range 1220Å to 1235Å.

Fig 1. Far ultraviolet spectrum of SS Cygni, showing the Lyman-α region at minimum and about 0.4 mag above minimum. The spectrum of DA white dwarf GD 394, scaled to SS Cygni, is shown by plus (+) signs.

3. DISCUSSION

For argument we assume that this feature is the red wing of a stellar Lyman-α absorption line whose center is filled in by geocoronal and disk emissions. Figure 1 shows that at quiescence (1984 Nov 22) the feature can be matched reasonably well by the red wing of Lyman-α observed in the DA-type white dwarf GD 394 (WD 2111+49). When the absorption profile is matched, SS Cygni’s continuum shortward of 1500Å also fits by the white dwarf. The white dwarf in SS Cygni has a V mag of about 15.9 if the agreement extends into the visual. The effective temperature of GD 394 is about 34,000 K.

The amount of interstellar extinction along the line of sight to SS Cygni is important in
the interpretation of the energy distribution. The 2200 Å feature can be used to estimate the extinction but these quiescent observations are not useful for this because of a low signal-to-noise ratio the data and possibility of distortion of the continuum by unnoticed or unresolved emission features. Therefore, we used four observations of SS Cygni in outburst obtained in 1978 and 1979 when the LWR camera, which has better signal-to-noise characteristics around 2200 Å, was used. Application of the technique of Holm and Cassinelli (Ref. 3) to these data yields \( E(B-V) = 0.04 \pm 0.02 \) (see Figure 2). In the following discussions the fluxes have been corrected for extinction.

Relative to GD 394, SS Cygni has a large flux excess in the middle ultraviolet. This is illustrated in Figure 3. The excess radiation can be modeled very well by a 9,000 K Planck function. If this Planck function is extrapolated into the visual, we find that it contributes about 75% of the light in the V band. It is tempting to associate this component with the hot spot where the accretion stream strikes the disk, since its temperature is reasonably similar to the 12,000 K hot spot of U Geminorum (Ref. 4). If so then the significant contributors to the quiescent continuum spectrum of SS Cygni are the white dwarf, the hot spot, and the cool, mass-losing component. The disk itself would be the source of the emission lines but would be an insignificant source of continuum radiation.

If we have detected the white dwarf, a distance to SS Cygni can be determined from the mass of the white dwarf, the mass-radius relationship for white dwarfs, the observed ultraviolet flux, and model atmospheres which predict the emergent flux in the ultraviolet. Unfortunately the mass is not known uniquely but only as a function of the inclination of the system. Figure 4 shows the dependence of distance on orbital inclination for the orbital elements determined by Cowley et al. (Ref. 5) and by Stover et al. (Ref. 6). Light lines represent upper and lower limits based on the uncertainty in the measurements, in the effective temperature, in the extinction correction, and in the IUE calibration.

In this picture supported by the appearance of the spectrum of SS Cygni as the star was approaching minimum on 1984 July 5? On that day the far ultraviolet was about twice as bright as at quiescence and, relative to the quiescence fluxes, showed a slight peak in the 1600 Å range. Thus, the higher fluxes appear to arise in a slightly cooler source. This is consistent with a picture in which a hot white dwarf gradually is revealed by the fading of the light from a disk which is cooler but of greater surface area than the star. On the other hand, the appearance of the 1220-1235 Å absorption feature does not change significantly between the two observations. This behavior appears to contradict our primary assumption that the feature arises in a stellar photosphere. The effect may be similar to the observation by Hessman (Ref. 8) that SS Cygni's Balmer line profiles remain constant during the decline from maximum.
SS Cygni in quiescence shows an absorption feature that might be photospheric Lyman-$\alpha$ from the white dwarf primary. This would be the first direct detection of this white dwarf. Analysis of the distance and the energy distribution are compatible with this interpretation. Unfortunately, the profile of the feature does not appear to change when the disk becomes as bright as the assumed white dwarf. This behavior shows that the disk itself can produce an absorption feature resembling that of a white dwarf and that the existence of the feature is not proof that the white dwarf has been detected.

5. REFERENCES


UV AND OPTICAL LINE EMISSION FROM THE SHELL OF THE OLD NOVA GK PERSEI

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ABSTRACT

UV line emission is found in spectra taken of the brightest region ("bar") of the shell of GK Per in 1987. This makes the remnant of the nova of 1901 the first classical nova nebula to have been detected in wavelengths from the radio region to the ultraviolet. Preliminary results suggest that the spectral line ratios can be fitted by a shock model under the assumption of an underabundance of hydrogen and an overabundance of nitrogen. The observed shock velocities in the range 100-200 km s⁻¹ are characteristic of reverse shocks entering the nova ejecta.

Keywords: Novae, Nova Shells, Abundances, Shock Model

1 Introduction

The optical appearance of the shell of GK Per is different from that of other bright nova nebulae. It is classified as irregular (Mustel and Boyarchuck 1970). Only recently it was found that the shell has the typical structure of nova ejecta: that of a prolate ellipsoid, with different characteristic emissions along the "equator" and near the "poles" (Seitter and Duerbeck 1987). The peculiarity of the optical shell can be described in terms of two parts missing: the south polar cap and that quarter of the ellipsoid which lies towards the east and on the near side (Duerbeck and Seitter 1987).

Radio observations of the shell showed that the radio emission is non-thermal and that the strongest isophotes coincide with the brightest optical part of the shell, the bar in the SW quadrant (Seaquist et al. 1988).

IRAS observations have revealed that GK Per is embedded in a very extended, regularly shaped cloud of cool dust. The dust is interpreted as part of a remnant planetary nebula ejected from the central object approximately 100 000 years before the nova outburst. This large dust cloud may also account for part of the light echoes of the nova outburst seen in 1901 and 1902 (Bole et al. 1987).

Unpublished optical spectroscopy led Williams (1981) to conclude that electron temperatures in the expanding remnant exceed 25 000 K. This, together with the emission of radio synchrotron radiation suggests, according to Seaquist et al. (1988), that the remnant of GK Per is akin to a miniature supernova remnant, excited by shock waves. The radiative shock model of Cox and Raymond (1985) provides line ratios which are very sensitive to different shock velocities when both ultraviolet and optical lines are available. This was one of the incentives to study the nebula in the UV despite the problems caused by its extreme faintness.

2 Observations

Optical CCD spectroscopy of the remnant was carried out in January 1987 with the 3.5 m telescope of the Calar Alto observatory.

Table 1 gives details of the UV observations, obtained with IUE in December 1987. Pre-determined offsets, measured from direct images, were used to point the satellite. Two locations were chosen. One is in the SW bar whose strongest optical radiation comes from the forbidden nitrogen lines. The bar is part of the "equatorial belt". The other location is the strongest emission blob near the "pole" in the NW. Here, the strongest lines are

<table>
<thead>
<tr>
<th>Date</th>
<th>Target</th>
<th>Camera</th>
<th>t_exp (hours)</th>
<th>optical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/12/87</td>
<td>SW</td>
<td>LWP</td>
<td>1</td>
<td>[NII]</td>
</tr>
<tr>
<td>18/12/87</td>
<td>SW</td>
<td>SWP</td>
<td>5</td>
<td>[NII]</td>
</tr>
<tr>
<td>20/12/87</td>
<td>NW</td>
<td>SWP</td>
<td>7</td>
<td>[OIII]</td>
</tr>
</tbody>
</table>

* Characteristic lines are given.
also the nitrogen lines, followed by Hα (which is very weak in the equatorial region) and the forbidden lines of O III. The O III lines are noticeably stronger than in the bar, which, however, displays quite strong forbidden O II and weak O I lines.

3 Preliminary Results

Flux-calibrated optical line ratios are given in Table 2, together with the model data and the corresponding shock velocities $v_s$. The first section of Table 2 lists the measured optical line ratios, corrected for differential interstellar extinction, using $A_V = 0.7$. The insufficient matching between the observed and the model data can be removed when we correct for the observed underabundance of hydrogen in the equatorial region by a factor 4.5, in the polar region by 2.5. The corrected data are given in the second section. In the third section a correction by a factor 3 is made for the noticeable overabundance of nitrogen in the bar region. Williams (1981) has also indicated such an overabundance.

Comparison with nuclear reaction models (Wiescher et al. 1986) suggests that the underabundances of H might be overestimated and that instead large overabundances for both oxygen and nitrogen should be assumed. This is not supported by the UV spectra.

Table 2. Optical emission line ratios.

<table>
<thead>
<tr>
<th>Optical line ratios</th>
<th>Bar (NW) $v_s$ km s$^{-1}$</th>
<th>Blob (SW) $v_s$ km s$^{-1}$</th>
<th>Model ratios</th>
<th>$v_s$ km s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O I/Hα,β</td>
<td>27</td>
<td>-</td>
<td>4**</td>
<td>130</td>
</tr>
<tr>
<td>O III/Hα,β</td>
<td>8</td>
<td>6</td>
<td>4.3**</td>
<td>119</td>
</tr>
<tr>
<td>N II/Hα,β</td>
<td>40</td>
<td>8</td>
<td>3**</td>
<td>119</td>
</tr>
<tr>
<td>O I/Hβ</td>
<td>7</td>
<td>-</td>
<td>2.2**</td>
<td>119</td>
</tr>
<tr>
<td>O I/Hα,β</td>
<td>6</td>
<td>130</td>
<td>6**</td>
<td>130</td>
</tr>
<tr>
<td>O III/Hα,β</td>
<td>1.6 $&lt; 119$</td>
<td>2.3 $&lt; 119$</td>
<td>2.3 $&lt; 119$</td>
<td></td>
</tr>
<tr>
<td>N II/Hβ</td>
<td>9</td>
<td>3.3</td>
<td>3</td>
<td>119</td>
</tr>
<tr>
<td>O I/Hβ</td>
<td>1.6</td>
<td>130</td>
<td>1.6</td>
<td>130</td>
</tr>
<tr>
<td>N II/Hβ</td>
<td>3</td>
<td>119</td>
<td>3</td>
<td>119</td>
</tr>
</tbody>
</table>

* Using $Hβ = \frac{1}{2}Hα$.
** Maximum ratios from Cox and Raymond models.
The SWP spectrum of the bar is shown in Fig. 1. There is no doubt that in spite of its weakness, the NV line at 124 nm is present. The line is also clearly seen on the photowrite, where it fills the 20" aperture completely. This indicates that the line is real and originates in an extended nebula. The total flux in the line is $8 \times 10^{-15}$ W m$^{-2}$ for $A_V = 0.7$. More tentative identifications of lines have been made for OIV, SiIV, 140 nm and NIII 175.0 nm. No lines were evident in the NW SWP exposure.

The total absence of Mg II in the long wavelength spectrum of the SW bar came as a surprise. The only hump that might qualify for an emission is near 283 nm, and if real, might be attributed to Ne III.

With all the caution justified by the weak and noisy UV spectra, we may nevertheless draw some tentative conclusions. Table 3 contains observed line ratios, assuming that the lines at 140 and 175 nm are real. The flux ratio of NV 124 nm to NIII 175 nm suggests, from the Raymond and Cox models, that $140 < v < 186$ km s$^{-1}$. In this case, CIV 155 nm would be expected to be stronger than NV. Its absence implies that N is overabundant with respect to C by a factor $> 8$. This is consistent with the absence of a strong CIII 190.9 nm line. The 140 nm line could be dominated by either OIV or SiIV. The absence of the O III 106.6 nm line suggests that the line is due to SiIV, so that in the bar N may also be overabundant with respect to O by a factor similar to that of C.

Table 3. Ultraviolet emission line ratios in the bar.

<table>
<thead>
<tr>
<th>UV line ratios</th>
<th>Observed Ratio $N(V/NIII) = 3 \pm 0.5$</th>
<th>Model Ratio $(400 \leq v \leq 186$ km s$^{-1}$)</th>
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<td>NV/CIII</td>
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* Absence of O III lines makes SiIV more likely.

4 Conclusions

The optical and UV data support the shock model for the excitation of the nebula of GK Per. The deduced velocities suggest that in the bar a range of shock velocities may be present. The velocities are in general agreement with those expected from reverse shocks entering the denser nova ejecta. The expansion of the remnant suggests forward shock velocities of order 1000 km s$^{-1}$. This in turn requires a density contrast between the optical and UV emitting blobs and the forward shocked gas of around two orders of magnitude.

An underabundance of hydrogen and an overabundance of nitrogen in the bar must be assumed - a deviation from solar abundances which is common for nova remnants. Simply correcting the present shock models for different abundances, while the resulting differences in cooling rates are neglected, gives, of course, only a first approximation of what is expected from the shocks. Shock models calculated for different abundances are clearly needed.

The absence of NV 124 nm in the very long exposure of the polar blob implies either that the shock conditions are different, or, more likely, that there are differences in chemical composition between the equatorial and the polar clouds, as suggested by the optical spectra.

The presence of neon lines in the optical and possibly in the UV spectrum is in good agreement with the fact that GK Per was indeed a neon nova, arising from a high mass white dwarf. This together with the concurrent absence of magnesium and the high abundance of N may help to narrow down the range of possible outburst models. The undeniably large underabundance of hydrogen apparent in the spectra is not accounted for in the models by Wiescher et al. (1986).

Acknowledgements

MFB acknowledges travel support and the provision of an Advanced Fellowship by the UK SERC. HWD acknowledges travel support by the Deutsche Forschungsgemeinschaft. Discussions with J.C. Raymond were most helpful. IUE data reduction was performed on the University of Keele STARLINK microvax using IUEDR.

References

We present low resolution IUE observations of the dwarf nova Z Cha during superoutburst. These cover most of the development of the outburst and have sufficient time resolution to probe continuum and line behaviour on orbital phase. The observed modulation on these phase is very similar to that observed in the related object OY Car. We interpret the results to imply the presence of a 'cool' spot on the edge of the edge of the accretion disk, which periodically occults the brighter inner disk. Details of the line behaviour suggest that the lines originate in an extended wind-emitting region. In contrast to archive spectra obtained in normal outburst, the continuum is fainter and redder, indicating that the entire superoutburst disk may be geometrically thicker than during a normal outburst.

1. INTRODUCTION

Z Cha is an eclipsing member of the SU UMa subclass of dwarf novae, which are characterized by the superoutburst mechanism and the 'superhump' phenomenon. Superoutbursts are brighter (0.6 mag in average) (Ref.1) than normal outbursts and last ~10 days. Although less frequent than normal outbursts, they are relatively speaking more predictable. In addition, an optical modulation, the 'superhump' appears after the superoutburst peak. In contrast with the quiescent orbital hump, the superhump systematically traverses the eclipses due to a period, 3-7 per cent longer than the orbital period. Z Cha displays a superhump with a period of about 111 min (orbital period: 107.3 min) and a beat period of 2.1 days. (Ref.2).

VW Hyi, although one of the best observed dwarf novae in the UV is harder to interpret than either of the two eclipsing SU UMa systems, OY Car and Z Cha, both of which have relatively frequent superoutbursts. OY Car was the subject of a multiwavelength campaign (Ref.3-4).

during which IUE observations were obtained resolved on orbital phase. These were the first to show distinct differences between eclipsing and face-on systems, and evidence for wind emission from a considerable volume in addition to the expected disc emission. Further observations on Z Cha, one of the cornerstones for dwarf nova studies, are crucial to investigate the superoutburst-superhump phenomenon. Although non-eclipsing SU UMa stars in superoutburst reveal bright blue continuum spectra with prominent absorption lines (IUE archive), differing from outburst spectra in overall flux level, Z Cha shows prominent emission lines as in its quiescent state. Here we present the first IUE observations of Z Cha in superoutburst which cover its overall development as well as providing good coverage of orbital phase on two dates.

Figure 1. Optical light curve of Z Cha during the 1987 superoutburst. Crosses + mark actual visual observations and circles o upper limits (VSS RAS NZ). Horizontal lines show length of IUE Observations (mean FES magnitude).
2. OBSERVATIONS

Figure 1 shows the light curve of Z Cha during the 1987 superoutburst. Crosses mark actual visual observations and circles upper limits from the VSS RAS NZ. The times of IUE and SAAO observations are marked. The length of IUE observations are shown by horizontal lines that lie at the mean FES magnitude. VSS RAS NZ points within the phase range 0.9-0.1 have been omitted to decrease the scatter introduced by the eclipses. The exact time of the beginning of the outburst is uncertain but the peak was reached at HJD 2446887.1 after a brightening of at least 2 mag in under 1.7 days. The outburst decayed slowly over the next 18 days with a rate ~0.13 mag/day.

The figure shows the timing of the IUE observations relative to the overall optical light curve. Low resolution spectra (28 swp and 11 lwp) were obtained utilizing the target of opportunity programme. On 31 March, 6 exposures gave a limited coverage of one orbital cycle. On 1 April, 2 exposures added to a total of 8 exposures during the rise and near the superoutburst peak. The remaining 5 exposures covered 3 orbital cycles and the 4th group of observations on 7 April with 9 exposures covered 4 cycles.

The IUE observations on 5 April are 4.5 days past superoutburst peak, so it is expected that the superhump had already developed. On 8 April, a complete orbital cycle of 8 filter photometry was obtained on the SAAO 1.0m telescope. From this run we estimate the superhump ephemeris.

3. IUE RESULTS

Figure 2 shows representative swp spectra from 1-2 April which have been arranged in order of orbital phase. The most prominent features are the strong emission lines which, except for eclipsing systems, are uncharacteristic for dwarf nova in outburst. Strong emission lines of Lyman Alpha(1215A), CIV(1550A), NV(1240A), SiIV(1400A), HeII(1640) are present one after another showing variability with orbital phase, both in strength and complex profile. Emission features at 1667A, 1594A, 1340A are evident as well as absorption lines SiIII(1300) and at 1608A, possibly FeII. The continuum is very weak in eclipse and the CIV profile loses its double peak structure (seen in out-of-eclipse spectra) becoming narrower and symmetrical. These spectra show asymmetry of CIV(1550) line away from eclipse, in the sense that the red wing falls more rapidly than the blue one. A structure at the left of the blue wing shows a stronger emission flux than the corresponding edge of the red wing, seen in eclipse too. This could be attributable to a weak blended line. Ly Alpha shows a double structure like the CIV line.

Spectrum swp30690 (phase 0.56-0.75) has a rather weak continuum flux compared to the other non-eclipse spectra which show a strong continuum. The continuum shows variability of the absolute flux on a time scale of hours, which could be caused by a thick, vertical structure at the outer rim of the accretion disk (stability timescale of a few orbital cycles). In contrast, the continuum is much weaker and redder during eclipse compared with non-eclipse spectra. Lwp spectra have a very weak continuum with no strong emission features except for some evidence for Mg II(2800A).

4. VARIATIONS ON THE ORBITAL TIMESCALE

The continuum flux for 1-2 April in the regions 1345-1360 A and 1470-1515 A is plotted as a function of orbital phase in Figure 3. The mean out-of-eclipse flux drops 80% at phase 0.0. In addition, Figure 3 shows a clear flux modulation over a large range of orbital phases. This smooth modulation peaks near phase 0.4 and has a minimum near phase 0.8 resulting in a final 50% drop in the continuum flux. Although the effect is less marked on other dates, it seems clear that there is cyclical modulation on the orbital timescale.

In Figure 4 we plot the strongest emission lines against orbital phase. The eclipse depth of C IV line is 20% of the out of eclipse mean flux. The total flux perhaps shows a smooth modulation. N V, Si IV, He II show eclipses of 30%, 65% and 70% respectively but not mid- phase orbital modulation, except N V for which a 17% variation is marginally significant.

The fraction of the line flux eclipsed at phase zero, is probably associated with material close to the centre of the accretion disc. (The apparent disappearance of the double-peaked structure supports this hypothesis). In contrast, modulation of the line flux away from eclipse indicates that a large emitting volume is involved, such as a wind or corona, comparable in size to the accretion Roche lobe.
From the rough superhump ephemeris, we estimate that the orbital phase of the peak of the superhump was about phase 0.8 on 5 April. This coincides with a peak in the UV flux, but rather a dip, rather similar to what was observed in the case of OY Car in superoutburst (Ref.4). There we interpreted the UV dip as the obscuration of the inner disc regions by the outer edges of the disc at certain orbital phases which were consistent with the location of a cool bulge (or dark spot) near the stream impact area. A future fuller discussion of the behaviour of Z Cha, because the observations cover a range of beat phases, will attempt to differentiate between superhump and orbital phase. However these observations have confirmed the result seen for OY Car, that the UV flux from the accretion disc in superoutburst is redder than in face-on systems, and variable on the orbital timescale. Both of these observations are consistent with the idea of an accretion disc with an opening angle of about 14 degrees, and some form of azimuthal structure.

Spectra from the recent normal outburst at Z Cha in January 1988 show a strong blue continuum in contrast with the redder continuum in the 1987 superoutburst. This is indicative of the different phenomena appearing. Although an outburst is thought to trigger the superoutburst (Ref.5), the latter lasts about 10 times as long, and is probably only sustainable if there is a prolonged burst of mass transfer from the red star. Under these conditions, the steady accretion of matter onto the white dwarf (and associated outward transfer of angular momentum) leads to the growth of the accretion disc. Whitehurst (Ref.6) has pointed out that in short period systems the mass ratio is such that the disc may become dynamically unstable at a smaller radius than the normal tidal truncation with the Roche lobe. He associates the additional dissipation due to this phenomena in a slowly precessing disc with the observed superhumps which we know to originate in a large fraction of the outer disc. We propose in addition, that this dissipation, particularly in the presence of a high mass transfer rate may lead to a puffing up of the outer accretion disc during superoutburst. Thus, in superoutburst, the disk appears bigger and thicker at the outer rim whereas it appears smaller and thinner in normal outbursts. The rather cooler flux distribution is a further evidence for an extended vertical structure. This is because in high inclination systems such as Z Cha, the central hotter regions are obscured by the large opening angle of the disk.
6. REFERENCES

Binary Stars, Circumstellar Matter & Mass Transfer
ABSTRACT

The UV observations of the Wolf-Rayet binary systems HD 97152 and HD 152270 are presented. Both systems contain a WR component, and both have relatively small orbital inclinations. Weak atmospheric eclipses at emission line wavelengths are detected in HD 97152, the system for which a more valuable phase coverage is available.

Keywords: Wolf-Rayet stars, binary systems.

1. INTRODUCTION

Strong, phase-dependent spectral variations have been observed in at least 7 Galactic WR+WR Wolf-Rayet binary systems in the UV wavelength range (1000-2500 Å). Of these systems, two contain WR stars, the rest having WR components (Ref. 1, 2). The dominant mechanism producing the variations in that of selective atmospheric eclipses of the brighter by the WR star's wind. Thus, the variable is strong in the systems with larger optical inclinations and/or smaller separations between the stellar components. The analysis of these systems can yield valuable information regarding the structure (i.e., \( V(r) \), \( n(r) \)) of the inner portions of the winds, behavior with large orbital separations and/or small orbital inclinations must be studied. Two such systems are HD 97152 (30W9+0.7) and HD 152270 (20W9+0.26), for which the complete set of orbital parameters has recently become available. Specifically, the orbital inclinations for both these systems (Ref. 3) have been derived through polarimetry measurements (Ref. 4).

In this paper we present the preliminary results of UV observations of HD 97152 and HD 152270. The objective of these observations was to determine the degree to which spectral variations resulting from atmospheric eclipses occur in these systems.

2. OBSERVATIONS AND REDUCTIONS

The observations were made in the low resolution mode, with the GIR camera, through the large aperture on 1986 July 23, 29, and December 5. Standard extraction and reduction procedures were employed. The GIR image mosaics and the Julian Dates of these observations are listed in column 1 and 2 of Table 1. The orbital phases, listed in column 3, were computed using the ephemerides of Davis et al. (Ref. 2) and the ephemeris (Ref. 7) for HD 97152 and HD 152270, respectively.

Equivalent widths were obtained with an Interactive graphing routine written by J.P. Harrill. The equivalent widths of the lines at 1939 \( (\mathrm{CIII}) \) 1771 \( (\mathrm{SiIV}) \) and 1540 \( (\mathrm{SiV}) \) are listed in Table 1. As in usual with WR stars, the location of the continuum level depends upon the criteria used for its definition. Here, the continuum level was chosen by visual interpolation between relatively line-free portions of the spectra, with special effort devoted to consistency. There is little ambiguity in the continuum levels at 1939 and 1540. However, there is shortward of 1540 it become very difficult to place the continuum. This is reflected in the error values associated with the measurements (Table 1). For the Si IV and C IV lines, while \( AV = 0.1 \) for the Si IV measurements, those values were obtained by varying the continuum level within reasonable limits.

In Figures 1 and 2 the spectra of HD 97152 and HD 152270 are illustrated. These have been constructed by averaging several spectra, in order to improve the quality of the signal/noise ratio. No reddening correction has been applied.

3. RESULTS

As expected from the low orbital inclination, strong phase-dependent variations were not detected in either of the two binary systems. The phase coverage for HD 152270 is sufficient, since spectra at orbital phase 0.5 are lacking. Thus, at this time, strong variations cannot be ruled out for this system. This is not the case of HD 97152, where, indeed, effects due to selective atmospheric
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Figure 1: IUE Spectrum of HD 97152.

Figure 2: IUE Spectrum of HD 15270.
GALACTIC WC + O BINARY SYSTEMS HD 97152 & HD 152270

The only change visible in the spectra of HD 97152 occurs in the profile of HD 97152 at 250 Å. These changes are shown in Fig. 3 where the low-profile ions from the universal H and O spectra, respectively, for given values of and . These changes could be distinguished at a level in wavelength for the orbital period of the 250 Å line (Fig. 3). These changes were noticed at the same time as the 250 Å line absorption feature, where the orbital separation is approximately 1.5 A. The orbital phase of the H & O lines, however, is much weaker than in HD 6563 (Fig. 4).

Figure 3: Ratio of spectra of HD 97152 corresponding to W-R "in back" divided by W-R "in front".

Figure 4: Profiles of the CIII] 1909 line at orbital phases 0.88 (dark tracing) and 0.55 (lighter tracing).

References:
Atmospheric Eclipse Effects in Wolf-Rayet Binaries in the Small Magellanic Cloud

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ABSTRACT

We present the results of UVE observations of three SMC WR binary systems. Selective atmospheric eclipse effects are evident in WR1980 (HD198060) and Sk 188 (V1057SM), but are very weak, or absent in Sk 108 (V504SM). The differences in heavy-metal content between the SMC and Galactic objects is clearly manifest in the lack of atmospheric eclipse effects in the wavelength range 1200-2000 Å in HD198060 and Sk 188.

Results and Discussion
Strong, phase-dependent variations were observed in HD198060 and Sk 188, similar to those which occur in the Galactic WR systems, and which are the result of selective atmospheric eclipses. These variations in the wind are those which are not synthesized in the early stages of stellar evolution.

A very useful tool for probing the wind structure in WR stars is that of selective atmospheric eclipse effects in three systems in which the companion (usually a luminous C-type star) traverses behind a portion of the wind of the WR star during its orbit. Thus, the intervening wind absorbs the continuous radiation of the companion at selected wavelength, the strength of the absorption being proportional to the column density of material. This mechanism was first identified by Mihalas (Ref. 1) to be responsible for emission-line profile variations in WR stars at optical wavelengths, and provided a tool for empirically determining wind characteristics (see Ref. 2 and references therein).

In a previous paper (Ref. 3) we reported the phase-dependent variations which occur in the UV (1300-2200 Å) lines of Galactic WR + O binary systems, where the atmospheric eclipses are very strong. This effect is most noticeable in the NIVuersity of Montreal V458 A line and in the wavelength region 1500-1650 Å, the latter being affected by absorption by HeII and He VI lines (Ref. 4).

We have extended this study to three WR binary systems in the Small Magellanic Cloud, where the ambient heavy metal abundances are significantly lower than those in the Galaxy. The objective of these observations is to determine whether selective atmospheric eclipses occur and, when they do, search for differences between the variability in the SMC and the Galactic binary systems.

The three systems studied are the brightest WR stars in the SMC: HD 2190 = AB4, Sk 108 = AB6 = R31, and Sk 188 = AB8. The observations consist of low-dispersion UVE spectra in the 1300-2200 Å wavelength range obtained with long enough exposure times to optimize count levels in the continuum near 1700 Å. A complete description of the observations will be presented elsewhere (Ref. 11).

2. RESULTS AND DISCUSSION

Strong, phase-dependent variations were observed in HD 2190 and Sk 188, similar to those which occur in the Galactic WR systems, and which are the result of selective atmospheric eclipse effects. These variations
As with the deltoideus and pectoralis muscle, the HD 5980 line profile shows a distinct broadening in the 0.15-1.60 AU region. This broadening is more pronounced in the 0.15-0.30 AU region, indicating that the absorption line is a result of an optically thick molecular cloud in the line of sight. The broadening is also more pronounced in the 0.40-0.60 AU region, suggesting a different structure in the cloud.

The only emission lines that are clearly present in the low-dispersion spectrum of HD 5980 are HD 18260, C IV 5803, and C II 1335. The very low line-to-continuum ratio is comparable to what is observed in the optical spectrum of this system, where the emission lines are very weak.

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primarily to a weak W-R wind. However, the orbital inclination is probably small, given the photometric eclipse effects.

3. CONCLUSIONS

The effect of atmospheric eclipse at emission line wavelengths in two of the three SMC binary systems studied are similar in nature to those which occur in Galactic W-R binary systems. The major differences is the absence of atmospheric eclipse effects in near-continuum regions formed by largely forbidden lines of Fe IV, Fe V or Fe VI lines. This is consistent with the lower heavy-metal abundances expected for SMC W-R stars as compared with their Galactic counterparts.

4. ACKNOWLEDGMENTS

We wish to express our gratitude to the IUE Observatory and HDFP staff for their assistance during the observation and reduction phases. A.F.J. acknowledges financial assistance from the Natural Sciences and Engineering Research Council of Canada. L.H.A. thanks the Department of Energy for support during this project.

5. REFERENCES


Figure 2. Ratios of IUE spectra of Sk 188. The spectrum in the denominator is SWP29634. The hatched regions mark the portions of the spectra which contain strongly saturated pixels.
MASS FLOW IN THE INTERACTING BINARY TX URBAN MAJORIS

G.E. McCluskey, Jr.  C.P.S. McCluskey  Y. Kondo
Lehigh University  The Pennsylvania State University  Goddard Space Flight Center

ABSTRACT

Twenty-two far-ultraviolet and twenty-three near-ultraviolet high resolution International Ultraviolet Explorer (IUE) spectra of the interactive Algol-type binary TX Ursae Majoris (B8 V + F-K III-IV) have been analyzed in order to determine the nature of the mass flow occurring in this system. Absorption features due to high-temperature ions of Si IV, C IV and N V are always present. The resonance lines of Al III, Fe II, Mg II and Si IV show strong phase and secular variations indicative of both gas streaming and circumstellar/circumbinary material. Radial velocities as high as ±500 to 600 km s⁻¹ are present. The system is more active than V Sagittae and about as active as U Cephei.

Keywords: Interacting Binaries; Mass Flow; Ultraviolet Spectra

1. INTRODUCTION

The eclipsing binary TX UMa = HD 93033 is a typical Algol-type binary with a period of 3.06 days. Swensen and McNinttara (Ref. 1) noted the presence of variable absorption cores in the Balmer series and attributed this to the presence of gas streams. Numerous photometric studies have been published (e.g., Refs. 2-4). Koch (Ref. 2) found that an extended atmospheric structure was present around one of the components. The photometric solutions are in reasonable agreement indicating that the cooler star is at its critical Roche lobe and is 1.6 to 1.8 times larger than the detached B8 V primary. The spectral type of the secondary component is uncertain with estimates varying from F2 to X5. The value of K₂, the velocity semi-amplitude of the cool component, is not known and the masses are consequently subject to considerable uncertainty. Kreimer and Tremko (Ref. 5) give ranges of 2.8 to 6.1 and 0.8 to 1.8 solar masses for the hotter and cooler components, respectively. They note variations in the depth of primary eclipse as large as 0.11; changes which are not symmetric with respect to phase zero. Oh and Chen (Ref. 6) concluded that a discrete period change of ±0.7 to ±0.4 days occurred in 1985 with the period essentially constant before and after that change. Such a period change could be accounted for by a mass transfer of 1.1 x 10⁻⁶ solar masses. Mallama (Ref. 7) and Gluriez et al. (Ref. 8) find that the primary star is rotating about three times faster than synchronous rotation would require. It is clear that TX UMa is experiencing mass flow with secular variations.

2. OBSERVATIONS

With the launch of the IUE satellite, it became possible to study mass flow in the ultraviolet spectral region where it has signatures far more observable than in the optical spectrum. In 1980 and 1981, nine high resolution IUE spectra of TX UMa were obtained. Polidan and Peters (Ref. 9) and Peters and Polidan (Ref. 10) have discussed some of these spectra as well as those of a number of other Algol-type binaries. They did not detect C IV or N V in TX UMa but noted the presence and phase dependence of the Si IV resonance doublet stating that it is absent at phase 0.60 in mid-1980 but that it is prominent at phases 0.07, 0.40 and 0.92 later in 1980 and very early in 1981. A gas stream is present at phase 0.92. They found AI III to show similar effects. It is concluded (Ref. 10) that a high temperature accretion region of variable strength and distribution is present in many Algol-systems. The presence of resonance lines of N V, C IV and Si IV in many of these indicates an electron temperature of 10⁸ K, and an electron number density of 10⁶ cm⁻³ with a concentration near the following hemisphere of the primary star.

Since TX UMa was obviously undergoing mass flow, McCluskey and Kondo (Program 15N1GM) obtained twenty-nine high resolution IUE spectra of TX UMa over one orbital period in June 1985 in order to study phase and secular variations of the mass flow in TX UMa. In addition, nine high resolution spectra were obtained by another program earlier in 1985. The total of forty-five high resolution spectra of TX UMa provided an excellent data set to examine the mass flow in this system. All phases were calculated using the light elements of Oh and Chen (Ref. 6).
3. DISCUSSION

Careful analysis of the data reveals that weak absorption features due to the C IV and N V absorption lines are present at all phases. Phase variations are minimal as are secular variations. The average equivalent widths are $0.39 \pm 0.17 \text{ Å}$ and $0.42 \pm 0.17 \text{ Å}$ for $\lambda 1238$ and $\lambda 1242$ of N V, respectively, and $0.38 \pm 0.12 \text{ Å}$ and $0.37 \pm 0.11 \text{ Å}$ for $\lambda 1568$ and $\lambda 1550$ of C IV, respectively. The velocities are subject to considerable uncertainty but for both C IV and N V, while showing variations in the sense of the orbital motion of the primary star, they show a bias of $-50$ to $-150 \text{ km}s^{-1}$.

The Si IV resonance doublet is always present in absorption but shows considerable phase variation. These lines were somewhat weaker at corresponding phases in 1980-81 than in 1985. The equivalent widths of both components of the doublet are $50-100\%$ stronger at phases from 0.78 to 0.97, with the exception of phases 0.83 and 0.93 which were obtained in 1980 and which are among the smallest values measured. There is also a slight ($\sim 30\%$) increase in equivalent width between phases 0.41 and 0.51, as well as at phases 0.077 which were obtained in early 1980. The radial velocities vary roughly with the orbital velocity of the B8 V star but show considerable scatter with a bias of $-50$ to $-100 \text{ km}s^{-1}$ between phases 0.0 and 0.6 and $+50$ to $+100 \text{ km}s^{-1}$ between phases 0.6 and 1.0. Significant longward absorption equivalent to as much as $+500 \text{ km}s^{-1}$ is present between phases 0.78 and 0.97. Shortward absorption as high as $-500 \text{ km}s^{-1}$ is present at phases 0.08 to 0.41. The longward absorption develops somewhere between phases 0.61 and 0.78 where no observations are available.

The Al III resonance doublet behaves very similarly to the Si IV doublet and it is very likely that they arise in close proximity. In the far-ultraviolet spectrum, the absorption lines of C II, Si II, and Al III, appear to be mainly photospheric showing little or no phase variation and yielding radial velocities consistent with the B-type primary star. The Fe III lines at $\lambda \lambda 1895, 1914, 1926$ show a modest increase in strength after phase 0.6 with little velocity bias.

The most prominent lines in the mid-ultraviolet spectrum are the resonance line of Fe II at $\lambda 2599$ and the Mg II resonance doublet at $\lambda \lambda 2795, 2802$. These are all affected by mass flow.

The Fe II resonance line shows increased strength at phases 0.86 - 0.97 with the exception of phase 0.94 observed in 1980 when it was similar in strength to its value before secondary minimum. There is longward absorption of $+300$ to $+400 \text{ km}s^{-1}$ at phases later than 0.8. The radial velocities indicate a negative bias of $-10$ to $-60 \text{ km}s^{-1}$ at all phases.

The Mg II resonance lines are strongly affected by mass flow, once again particularly after phase 0.77. Longward absorption increases dramatically between phases 0.53 and 0.77. Longward absorption extends from $+450$ to $+500 \text{ km}s^{-1}$ after secondary minimum. The shortward absorption to $-300 \text{ km}s^{-1}$ is present from phase 0.07 to 0.44. Once again the radial velocity varies in the same sense as the primary star and in this case shows no systematic bias toward positive or negative velocities. No emission is detectable in any of the spectra and no strong narrow absorption components appear although weak components may be present in Si IV, Fe II and Mg II in the 0.7 - 1.0 phase range. Continuum intensity measurements were made at numerous wavelengths at all phases. Except for the expected decrease in intensity in primary eclipse no significant ($\geq 5-10\%$) variations were noted.

It is clear that extensive mass flow is occurring in TX LMa. It is relatively widespread with a concentration of material visible between phases 0.7 and 0.1. The relatively changing strength of the C IV and N V lines together with a systematic velocity of $-50$ to $-150 \text{ km}s^{-1}$ would seem to imply that these lines are formed at a greater distance from the B-star than are the Al III, Fe II, Fe III, Mg II and Si IV lines. They are probably formed in an expanding volume of gas with some degree of spherical symmetry. Whether this material is circumstellar about the B-star or circumbinary is not clear but line widths indicate some turbulent broadening which might be more readily explained by the circumstellar case.

The behavior of the Al III and Si IV resonance lines is so similar that they must form in the same region. Extreme radial velocities of $-300 \text{ km}s^{-1}$ and $+500 \text{ km}s^{-1}$ are present at phases 0.1 - 0.4 and 0.7 - 0.9, respectively. Both ions show a systematic velocity of $-50$ to $-100 \text{ km}s^{-1}$ in the 0.0 - 0.3 phase range and $+50$ to $+100 \text{ km}s^{-1}$ in the 0.6 - 1.0 phase range. The spectrum of excess absorption shows that narrow gas streams are not responsible but that a more diffuse flow is present. At phases 0.0 - 0.6 we detect gas which has circled around the B-star and is approaching the observer, while at phases 0.6 - 1.0 gas falling onto the B-star is detected. This also accounts for the great strength of the lines after secondary eclipse since only part of the gas will succeed in circling the B-star and causing the absorption after primary eclipse. The extreme velocities strongly imply that some material is escaping from the system. The Fe II and Mg II resonance lines are more difficult to interpret since significant interstellar and photospheric contributions are superimposed on the overall lines. The Fe II line shows extreme velocities of $-300$ to $+400 \text{ km}s^{-1}$ in the same phase relationship as that for Si IV and Al III. Similarly, the Mg II doublet shows a range of $-300$ to $+550 \text{ km}s^{-1}$. No consistent velocity bias greater than 20 km$s^{-1}$ is detectable. The Fe II $\lambda 2599$ line shows a small bias of $-10$ to $-80 \text{ km}s^{-1}$ at all phases. The Fe III lines show no bias in velocity but are clearly stronger after secondary eclipse.

The Al III, Fe II, Fe III, Mg II and Si IV lines, minus any photospheric contribution, are formed relatively close to the B-star and are part of the diffuse flow surrounding the B-star but concentrated on its following hemisphere. The picture of mass flow in this system is remarkably similar to that found in UX Cephei by Kondo et al. (Ref. 11). As noted by McCluskey and Kondo (Ref. 12) for U Sagittae, it appears that a "pseudophotospheric" region surrounds the B-star with a concentration on the following hemisphere. This region is created and energized the the interaction of gas from the cool companion falling onto the B-star. The "pseudophotospheric" lines of Fe II, Mg II and Al III are relatively broad compared with photospheric lines of Si II and Si IV but
have larger residual intensities. Since the continuum of TX UMa is unaffected by the "pseudo-photospheric" gas, a covering factor phenomenon such as observed for U Cep in outburst (Ref. 13) is unlikely. As suggested by Peters and Polidan (Ref. 10) turbulence is a likely factor in broadening these lines. The accretion of gas from the cool star by the B-star also accounts for the considerably faster than synchronous rotation of the latter.

4. CONCLUSIONS

The interacting binary TX UMa is in a state of active mass flow. In fact it is at least as active as U Cep when U Cep is in its "normal" state. The nature of the flow is quite similar to that of U Cep and, although stronger, to that of U Sge.

It is strongly desirable to obtain more accurate information concerning the secondary component, particularly its velocity semi-amplitude and spectral type. Infra-red measurements during the deepest part of the partial primary eclipse should help to resolve this problem. Since TX UMa mimics U Cep in many ways, it should be regularly monitored for outbursts similar to those of U Cep. In order to better understand the nature of the mass flow and evolution of the Algol-type systems, it is important to find systems undergoing active stages of mass flow. TX UMa is such a system.

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5. REFERENCES

A NEW STUDY OF THE INTERACTING BINARY STAR V356 SGR

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ABSTRACT

In this paper we present new results on V356 Sgr from IUE and Voyager ultraviolet (500-3200 A) observations obtained in 1986 and 1987, primarily during two total eclipses. The eclipse of 15 Aug 86 was fully covered with IUE low dispersion images and 9 hours of Voyager UVS data. The eclipse of 25 Mar 87 was covered with IUE low dispersion images and 1 high dispersion SWP image. During both eclipses the total strength of the emission lines were found to be invariant. Also, an uneclipsed UV continuum was detected at wavelengths shorter than 1500 A. The high dispersion SWP spectrum revealed that the emission lines are extremely broad, almost symmetrical emissions with weak, slightly blue shifted absorption components. No evidence of carbon, C I, C II, C III, or C IV, is seen in the emission or absorption spectrum of V356 Sgr in eclipse. Models for this binary system are presented.

Keywords: Interacting Binary Stars, Ultraviolet Emission Lines, CNO Processing, Ultraviolet Spectroscopy

1. INTRODUCTION

V356 Sgr is a massive eclipsing binary with a period of 8.896 days and a total eclipse of 11 hours duration. Both components of the binary are spectroscopically visible in the optical. Eclipse depths in V are 0.87 and 0.39 magnitudes, respectively, for primary and secondary minimum. Period changes suggest a steady, very low rate of mass transfer (~10^-7 M⊙ yr^-1) is occurring within the system. V356 Sgr also has some of the best determined physical dimensions of any interacting binary (Ref. 3). Table I lists the physical characteristics of the binary. The binary is moderately reddened, with an E(B-V) as determined from the individual colors of the components and from the 2200 A feature of 0.23±0.03 magnitudes. The most quoted model for V356 Sgr is that proposed by Wilson and Caldwell (Ref. 6). In this model they propose the existence a thick, opaque non-luminous ring (Ref. 7). The characteristic temperature of the UV excess is comparable to or slightly cooler than that of the B3 star (-16500 K from outside the domain of the B3 star or be of significantly larger radius than the A2 giant. Analysis of the shape of the flux excess argues in favor of the extended region. Figure 1 shows the Voyager and IUE spectra V356 Sgr outside and during the total eclipse. In this figure the eclipse spectrum is compared to the scaled and reddened spectrum of 38 Lyn, an A3 star, and to a synthetic spectrum obtained by combining the scaled and reddened 38 Lyn spectrum with a simulated electron scattering of the system light. This "scattered light" spectrum was obtained by taking the observed maximum spectrum and

2. OBSERVATIONS

The new IUE and Voyager UVS observations were obtained in 1986 and 1987, with most of the data taken during two total primary (when the B3 star is occulted) eclipses. The eclipse of 15 Aug 86 was covered with 12 SWP and 8 LWP IUE low dispersion images and 9 hours of Voyager UVS data. The eclipse of 25 Mar 87 was covered with 7 SWP and 6 LWP IUE low dispersion images and 1 high dispersion SWP image. No Voyager UVS data was obtained during this March eclipse. Additional IUE SWP and LWP low dispersion images were obtained after the two observed eclipses. Supplemental Voyager UVS data were obtained prior to the eclipse on 15 Aug 86 and in May 87.

3. OPTICAL LIGHT CURVE

The IUE FES was used to obtain an optical light curve for the eclipses in V356 Sgr. The FES light curve suggests two conclusions: 1) The quadratic ephemeris of Hall, Henry, and Murray (Ref. 1), 243900.766 + 8.896106E + 3.5x10^-2E^2, best fits the data. The significance of the second order term is confirmed. 2) There is suggestive evidence of changes in the shape of the eclipse light curve from the two FES light curves.

4. ULTRAVIOLET LIGHT CURVE

UV light curves were generated from the low dispersion images in three narrow (25 A, 65 A, and 250 A) continuum bands in the UV. These three light curves and the FES light curve were ratioed to the observed flux (appropriately scaled and reddened) of the A3 star 38 Lyn. The 1908 and 2625 A light curves appear relatively normal. The 1262 A curve, however, showed a substantial excess over that expected. During the total phase of the eclipse the B3 star can contribute no flux. So this UV excess cannot arise in the B3 star. Voyager 500-1200 A observations produced only a marginal detection of V356 Sgr during eclipse. This suggests that the characteristic temperature of the UV excess is comparable to or slightly cooler than that of the B3 star (~16500 K from outside of eclipse UVS observations). Since the source of the flux is (predominantly) unexplained by the A2II star it must either arise outside the domain of the B3 star or be of significantly larger radius than the A2 giant. Analysis of the shape of the flux excess argues in favor of the extended region. Figure 1 shows the Voyager and IUE spectra V356 Sgr outside and during the total eclipse. In this figure the eclipse spectrum is compared to the scaled and reddened spectrum of 38 Lyn, an A3 star, and to a synthetic spectrum obtained by combining the scaled and reddened 38 Lyn spectrum with a simulated electron scattering of the system light. This "scattered light" spectrum was obtained by taking the observed maximum spectrum and
Figure 1. Observed Voyager and IUE spectra of V356 Sgr at maximum and during the total eclipse of the B3V star. An IUE spectrum of a A3 reference star, 38 Lyn, scaled to the visual magnitude of the A2II component in V356 Sgr and reddened by 0.23 magnitudes in B-V is also shown. Also shown is a synthetic spectrum obtained from summing the scaled and reddened 38 Lyn spectrum with one percent (1%) of the observed maximum light V356 Sgr spectrum (Voyager plus IUE) smoothed to simulate electron scattering. Note the surprisingly good agreement between the synthetic spectrum and the observed V356 Sgr primary eclipse spectrum.

Figure 2. Si IV 1400 line strength as a function of phase during the eclipse of 15 Aug., 1986.
A NEW STUDY OF V356 SGR

V356 Sgr in Eclipse: C IV region

Figure 3. a) Emission lines of N V A1238 and 1242 (at +964 km s⁻¹ in this velocity plot), Si IV A1393, and Si III A1206 from the high dispersion SWP image obtained during the eclipse of 25 March, 1987. Dotted lines are drawn at ±V_eclipse for the B3 star. b) The C IV A1550 region from the same high dispersion image. Dashed curve is the spectrum of the A2III reference star ζ Sgr. Note the absence of any detectable C IV line. Dotted line is drawn at the expected level of the scattered light shown in Figure 1.

V356 Sgr: A2II star

Figure 4. a) Region of the expected strong photospheric C I line in the A2II component in V356 Sgr. The dashed curve is the spectrum of the A2III reference star ζ Sgr. Note the complete absence of a carbon line in the A2II star's atmosphere. The sharp C I line is the interstellar component. b) Photospheric C III A1247 and Si II A1264 equivalent widths for the B3V component in V356 Sgr and five non-binary stars of similar spectral type.

V356 Sgr: A2II Star

Figure 5. The Al III A1860 region in the eclipse spectrum. The dashed curve is the spectrum of the A2III reference star ζ Sgr. Note the Al III emission and the total absence significant absorption of the A star photospheric light at the central absorption core of the Al III lines.

Figure 3a

Figure 4a

Figure 4b

Figure 5
smoothing it with a 20 Å boxcar smoothing function. As can be seen in Figure 1 an excellent fit is obtained to the observed eclipse spectrum by assuming one percent (1%) of the total system light is scattered in the line of sight during eclipse. Thus, the origin of the flux excess appears to be electron scattering from an extended cloud surrounding the system.

5. ULTRAVIOLET EMISSION AND ABSORPTION LINES

Using the data obtained from the low dispersion images it was discovered that the total strength of the UV emission lines was invariant during both eclipses (Figure 2). This suggests that the line formation region is outside the immediate domain of the two stars in the binary and suggests a possible association with the region responsible for the scattered light. The high dispersion IUE spectrum obtained in March, 1987 revealed that the emission lines are extremely broad, FWHM ~1100 km s⁻¹, almost symmetrical emissions with weak, slightly blue shifted absorption components (Figure 3). Also, apparent in the high dispersion IUE image is that the "C IV" emission line reported in previous investigations is not the carbon doublet but rather dissolves into numerous weak emissions of, probably, Fe III. No evidence of carbon, C II, C III, or C IV, is seen in the emission spectrum of V356 Sgr during eclipse. Line profile fits to the emission line data suggest that all lines can be fit with the same line shape parameters. No evidence supporting a stratified line formation region was found. The strength of the carbon emission lines C II, C III, and C IV) in V356 Sgr are at least a factor of ~twenty weaker than the silicon (Si II, Si III, and Si IV) lines. Similarly, no evidence is found for carbon in the photosphere of the A2II star in V356 Sgr (Figure 4). Inspection of the high dispersion non-eclipse IUE images of V356 Sgr reveal a relatively normal B3/B4 stellar spectrum, including carbon lines. Figure 4 also presents data on the relative strengths of the photospheric C III λ1247 and Si II λ1264 lines for V356 Sgr and a set of B2.5 to B5 stars with similar rotational velocities. It is quite apparent that the C III line is of at least normal strength, indeed for its spectral type the C III line in V356 Sgr appears somewhat stronger than expected. Thus, we must conclude that the B3V component of V356 Sgr has an essentially normal carbon abundance while the A2II star has no observable carbon. How are these two carbon line observations compatible? Simple arguments (cf. those presented for other binaries in Ref. 2) can show that the secondary (A2II) star has likely lost enough mass to have reached its CNO processed layers. These layers will be virtually devoid of carbon and slightly nitrogen rich (cf. Ref 2). Thus, a compositional difference is expected to exist between the two components of the binary system.

One final question remains: what is the geometrical distribution of the high ionization gas? Figure 5 shows the Al III emission lines superposed on the photosphere of the A2II star. Despite the obviously saturated central absorption of the Al III lines no significant absorption of the A star's photospheric light is detected. Thus, the line formation region must be outside our line of sight, i.e. outside the orbital plane. Similar results are obtained for Si III and the scattered light continuum (Figure 3).

6. MODEL

Shu (Ref 5) has proposed a model for a "magnetically assisted accretion driven" wind for critically rotating pre-main sequence stars. His model can, with little modification, be directly applied to V356 Sgr. Carbon poor material will be transferred to a small accretion disk surrounding the B3 star. Using Shu's arguments, a portion (~75%) of this disk material will be accreted by the B3 star with the remainder being driven away in a wind with a characteristic velocity near the escape velocity of the B3 star and a preferential direction away from the orbital plane. Thus, this model predicts a gas outside the orbital plane with the chemical composition of the secondary but the velocity characteristics of the primary.

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7. REFERENCES


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MATTER STREAMS IN SEMI-DETACHED BINARY SYSTEMS

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ABSTRACT

The gas stream between the two components of CX Draconis is observed in the UV and subsequently modelled using a simple ballistic code. To scale the model to the data, an inclination of 15° is required. A jet of high velocity material is also present but cannot be accounted for with the aforementioned model. It is conjectured that viscosity will cause the infalling stream to spread to the extent that it can avoid collision with the photosphere of the primary and escape from the system by a gravitational 'slingshot' effect.

1. INTRODUCTION

The Be star CX Draconis (HD 174237, HR 7084, B2.5 Ve + F?) was first identified as a close binary undergoing mass transfer by Koubsky [4]. Subsequent observations at UV wavelengths have revealed a stream and a large ionization region [6], and X-ray observations [2] identify CX Draconis as an X-ray source but fail to link this to the matter stream. Coté and Waters [1] note an IR excess at 12μ as measured by IRAS and proceed to model a circumstellar disc.

The existence of the stream and surrounding material has been unambiguously established but the distribution of the transferred matter remains unclear. In particular, the IUE data analysed here reveal for the first time, a jet of material which escapes from the system.

2. THE DATA

Forty IUE images of CX Draconis covering several hundred orbital periods have been extracted from the RAL Archive and processed with the IUEDR software at UCL. Variations in velocity, line depth, and profile of AlIII, SiIV and FeIII (UV34) are seen to be strong, repeatable functions of orbital phase. The velocity curve (figure 1) has several interesting features. Firstly, it leads the orbital velocity of the B-star by ~ 90°, indicating that the absorbing material is not part of either star. Secondly, some of the profiles have multiple components (figures 2 and 3) whose velocity shifts imply that the matter is escaping from the binary system altogether, and thirdly, some of the lines are not in the 2:1 ratio expected for optically thin material implying that there is a great deal of matter surrounding the stars in the binary system. It is therefore postulated that not only is the secondary of CX Draconis undergoing mass-transfer via Roche lobe overflow, but that the stream thus formed is circling the primary and absorbing sufficient angular momentum from the orbital motion of the primary to escape from the system.

3. MODELLING THE STREAM

To construct a model of the stream in CX Draconis, the equations of motion of a test particle in a binary potential were numerically integrated to produce the ballistic trajectory of a stream of non-interacting material. This was then used to construct a radial velocity curve of the projected stream, viewed at an inclination i, as a function of orbital phase. The smooth curve drawn through the data is for an orbital inclination of 15° (figure 1). The accuracy of the fit is reduced because to calculate the predicted radial velocity, the point along the stream at which it first occults the primary is required, and due to the rotational distortion of the B star, this value is poorly known. However, the general fit is acceptable.
Figure 1: Superion & stream $V_r$ vs. phase in CX Dra

![Graph showing radial velocity vs. phase for CX Dra]

- Triangles: SiIV (1393a)
- Triangles: SiIV (1393b)
- Circles: AlIII (1854a)
- Circles: AlIII (1854b)

Figure 2: SiIV stream & photosphere in CX Dra

![Graphs showing residual flux vs. wavelength for SiIV stream and photosphere in CX Dra]

- Various wavelengths are labeled with corresponding residual flux values.
Figure 4: $V_{\text{max}}$ vs. $b$ for $\mu = 0.761$ (CX Dra)
4. THE JET

The data also contain evidence, in the form of line components with large blueshifts, for a rapidly-moving jet of material which leaves the system at a phase $\phi \sim 0.25$. To test the feasibility of having a stream launched by thermal overflow at the L1 point, the maximum attainable velocity $v_{\text{max}}$ and minimum approach distance to the primary $b$ of an infalling stream were computed as functions of the launch speed and launch angle (measured clockwise from the line joining the stellar centres). The resulting grid is shown in figure 4. The dotted lines represent the estimated radius of the star and the escape speed of the system in dimensionless units [5], so for a thermally-launched stream to successfully escape the system, it must have launch parameters which lie in the upper right-hand quadrant of the diagram, i.e. it must be launched at supersonic speeds and in directions which are not along the axis of symmetry of the system. The latter condition is easily fulfilled as the stream is always deflected by the coriolis force by an angle between $19.5^\circ$ and $28.4^\circ$ as it leaves the L1 point [5]. The former condition is not so easy to satisfy.

5. DISCUSSION

At first sight, it seems that a supersonic ejection mechanism is required to produce the observed stream (Kondo and M'CLUSKEY propose shocks generated by rotational splitting of propagating g-modes in U Cep as one possibility [3]). However, it should be remembered that the simulation is of the simplest possible nature and has totally ignored such effects as viscosity, shocks, turbulence and magnetism. Prendergast and Taam [7] include viscosity as a thermalization process occurring over a predetermined flow length and their model produces a jet of material which, having been supported by viscous transport of angular momentum, overshoots the stellar horizon and escapes. Work is now underway to produce a model of such a flow in the manner of PRENDERGAST and TAAM, and to test this model against observations in both the UV and the optical. Furthermore, the viscous model predicts that in addition to the stream and the jet, there exists a disc of circumstellar material at low densities, which is presumably responsible for both the Hα and IR emission, and that there is a component of the jet which falls back onto the leading hemisphere of the primary. This turbulent region is probably responsible for the scatter in the velocity curve about the model (figure 1) at a phase $\phi \sim 0.75$.

6. REFERENCES

ABSTRACT

We confirm that HR 2554 (G6 II + A0 V) is an atmospheric eclipsing system of the ζ-Aur type. IUE observations of the November 1987 eclipse indicate that the eclipse of the A star lasts about 4 days and is not total. Absorption lines due to the extended atmosphere of the primary can be seen a day before and after the eclipse and are missing 2 days from first and fourth contact. Thus the outer envelope of the primary extends to less than 1 stellar radius beyond the photosphere. Compared to 22 Vul (G3 Ib-II + B9 V), where the absorption can be traced to a few stellar radii, HR 2554 is a more moderate case of mass outflow, which implies there is reduced interaction of the secondary within the wind from the primary as is seen in the other ζ-Aur systems.

1. INTRODUCTION

In Ref. 1, we announced that the 195 day spectroscopic binary HR 2554 was a possible member of the ζ-Aur class of eclipsing stars. ζ-Aur systems usually have K to M type primaries, although this is a selection effect due to the fact that in the optical region the contrast between the components with earlier type primaries is smaller. For HR 2554, the primary is a G6 II star, and from the IUE observations, the secondary is of type A0 V, visually about 3.0 mag fainter. We have obtained IUE observations of the predicted November 1987 conjunction and confirm that atmospheric eclipses do occur. We discuss here some early results and compare them to the first recognized ζ-Aur system with a G-type primary, 22 Vul (refs. 2-3).

2. LOW DISPERSION OBSERVATIONS

As is typical for these systems, the circumstances of the eclipse depend upon the wavelength examined. The light from the secondary dominates up to 2800 Å, so few photospheric lines from the primary shortward of this are seen far from eclipse. In regions where low level lines are found, such as those for Fe II and Cr II, the eclipse of the secondary passing behind the G star’s outer atmosphere will appear deeper than in relatively line-free regions. In addition the eclipse should last longer in the lines depending on the extent and physical conditions of the outer envelope of the primary, including distances far from the surface where the stellar wind of the primary could be seen.

In figure 1 we present observations of HR 2554 made at four bandpasses, 2 “continuum” points at 3150 and 1850 Å, and 2 areas strongly affected by Fe II, 2550 and 1650 Å. As can be seen, the eclipse duration apparently is about 4 days. Because of uncertainties in the orbital solution, the ingress phase was not well-covered, and at the deepest observed part, the eclipse of the secondary was not total. If we include the observations...
of the Oct. 1986 conjunction and assume that the eclipse is symmetric and repeatable, we find that our deepest observations did occur at centrality, and thus the system is a grazing one. We find that this conjunction occurred at JD 2447117.45. The depth of the eclipse in V, as obtained from the FES measures, was 0.04 mag.

As expected, we find that the eclipse does begin earlier and end later in the Fe II bandpasses, but not as long as in 22 Vul where the 2550 and 1650 Å partial phases last about 10 days (Ref. 2). Furthermore, the depths in these regions are not as great prior to geometrical eclipse as for 22 Vul, indicating that the outer envelope for HR 2554 is not as large or dense as in 22 Vul. Some of this difference arises because 22 Vul is a somewhat longer period system (249 days) and the primary is a supergiant compared to a bright giant for HR 2554, but based on the diameters of the components, the added absorption lines in HR 2554 extend less than one stellar radius from the surface, while for 22 Vul absorption is seen for several radii.

3. HIGH DISPERSION OBSERVATIONS

The results of the low dispersion observations can be better understood when studying the absorption line spectrum at high dispersion. In figure 2 we show the temporal variation of the region around the Fe II multiplet 1 lines. Two days prior to first and after fourth contacts, only narrow interstellar components of the Fe II lines are seen. At partial phases the lines become stronger, but their structure remains relatively simple. At centrality, the lines deepen further and are still seen since the eclipse is not total, but no unusual behavior is displayed.

In contrast, the lines of 22 Vul show multiple components and some P-Cyg features due to the interaction of the hot secondary in the wind (Ref. 3). At centrality, forward scattering of the light from the eclipsed B star causes some lines to appear in emission. HR 2554 does not exhibit these anomalies.

Figure 2. LWP high dispersion observations of the November 1987 eclipse of HR 2554. Each succeeding spectrum is offset by $5 \times 10^{-12}$ ergs/cm$^2$/sec/Å. Fe II multiplet 1 line positions are labelled. Dates are differences from centrality at JD 2447117.45.
The reason for these differences can be gathered from the Mg II profiles, shown in figure 3. 22 Vul has a dense, high velocity wind component indicating the primary is providing substantial circumstellar material within which the hotter companion moves. At each observed line of sight, a range of velocities is sampled, and any density fluctuations appear as multiple components in the absorption lines. Emission features appear from a shock front at the B star since it is moving supersonically through the material. For HR 2554, the wind is of lower velocity and is less dense so that the outflowing material is more tightly bound to the primary. The range of velocities sampled along a line of sight is smaller, and there is little interaction between the wind and the hot star.

Further optical observations are needed for this system to determine the parameters of the eclipse and derive absolute dimensions. Currently the eclipses occur when the system is either far east or far west of the meridian in the evening. With a period that is 2 weeks longer than 6 months, the system should become more favorable for ground based observers. If the eclipse had been total, we predicted AB would be 0.14 mag, and AU, 0.27 mag. Based on the IUE observations, these should be reduced to 0.09 and 0.17 mag respectively.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

ASYMETHY IN ZETA AURIGAE CHROMOSPHERES

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IUE Archival Researcher

ABSTRACT

The zeta Aurigae systems provide an opportunity to study the lowest levels of supergiant primaries. At phases very close to ingress and egress the radiation of the hot secondary passes through layers of the late supergiant primary dense enough to shield them from ionizing radiation, but not so dense as to absorb the background continuum seen in the SWP camera. The combined effects of continuum and line absorption is to reduce the total amount of radiation in the ultraviolet--i.e., an atmospheric eclipse. Parsons, Ake and Hopkins (Ref. 1; henceforth PAH) produced evidence that the atmospheric eclipse of the zeta Aur system 22 Vul is asymmetric. The eclipse of zeta Aur itself has long been known to exhibit asymmetry and variability in optical observations. We look for IUE evidence of asymmetry in these two zeta Aur-type systems.

Keywords: Stellar chromospheres, Binaries, stellar rotation.

1. INTRODUCTION

Zeta Aurigae eclipsing binaries consist of a hot main sequence star orbiting a late-type supergiant primary. The dwarf companion makes a good probe of the primary's extended atmosphere. Optical observations to probe the lower chromosphere in this fashion have demonstrated that the lower chromosphere is asymmetric and the scene of considerable variability between orbits (Ref. 2). The secondary's continuum, which dominates at ultraviolet wavelengths, is especially valuable as a probe of the primary's atmosphere in the case of observations made with IUE, where the continuum spectrum is completely dominated by the secondary.

Previous observations of the continuum of 22 Vulpeculae have demonstrated that the ingress and egress sides of the eclipse are not symmetric. PAH found that comparing the intensity of integrated radiation in 50 A bands in the far UV between comparable ingress and egress phases suggested a strong asymmetry in 22 Vul. This effect is particularly pronounced in the vicinity of 1650 A. Absorption in the ultraviolet is due not only to continuum absorption, but also to absorption from numerous lines, especially those due to Fe II (see Figure 1). Given the strong asymmetry already reported in zeta Aur based on the optical observations, attention should be paid to the question of asymmetry in the UV as well. Although this task is complicated by the fact that zeta Aur has been only sparsely observed at egress, we here make a preliminary report on this question, as well as presenting new observations of 22 Vul supporting PAH's previous conclusions.

2. OBSERVATIONS

We have reported the discovery in IUE observations of the presence of narrow, strong low-temperature absorption lines due to Cl I, C I, N I, O I, and Ni II in 31 Cygni (Ref. 3), 22 Vul and zeta Aur (Ref. 4). These lines, observed approximately one week after egress and before ingress, respectively, of the blue dwarf component eclipse behind the cool supergiant, were attributed to the coolest part of the reversing layer. Such lines are produced by the shining of the hot dwarf companion's continuum through the edge of the supergiant's so-called "reversing layer" (near the temperature minimum), provided that the source region is sufficiently shielded from the ionizing radiation of the hot dwarf companion (Ref. 4). In the case of zeta Aurigae such lines have been well observed at ingress but not at egress.

We here report two observations of zeta Aur which we obtained on Jan. 18, 1988 (SWP32744H and SWP 32745H) and compare them to nine IUE archived observations. The complete list of observations is given in Table 1a. High resolution observations are indicated by an 'H' suffix and low resolution by an 'L' suffix. In addition we report five new observations of 22 Vul which we discuss along with thirteen observations previously reported by PAH. A list of the 22 Vul observations is given in Table 1b. All observations were made with the large aperture. Data was reduced and analyzed at the IUE RDAF in Greenbelt on the IUE VAX.

In Figure 1 we have plotted the wavelength band around 1650 A for the two observations of zeta Aur corresponding to phases +0.44 and -0.42. The phases were determined using the period and mid-eclipse epoch taken from Wood (Ref. 5):

\[ JD 2432553.666 + 972.162 'E \]  

where E is the number of orbits since the eclipse.

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Figure 1. Flux in units of ergs/s/cm²/A of Zeta Aurigae at the phases indicated. Solid line is from observation SWP7054H (Nov. 1, 1979); crosses from SWP32746H (Jan. 18, 1988).

Figure 2. Integrated Zeta Aur flux in wavelength range 1625 Å to 1675 Å in units of $10^{-12}$ ergs/s/cm² plotted against absolute phase.
ASYMMETRY IN ZETA AURIGAE CHROMOSPHERES

3. CHROMOSPHERIC ASYMMETRY

Our objective is to determine whether the amount of chromospheric material between us and the B star differs between ingress and egress. A plot of the integrated flux of Zeta Aurigae from 1625 Å to 1675 Å as a function of absolute phase shown in Figure 2 shows no significant difference between the ingress and egress phases. This seems puzzling in view of the asymmetries reported in the optical spectra. A direct comparison of this part of the spectrum shown in Fig. 1 from two small aperture observations suggests that there are differences between phases -0.042 and +0.044 in terms of the strengths of various absorption lines—some stronger at ingress and others at egress. Unfortunately, small aperture spectra cannot be used to compare the continua because sensitivity to pointing accuracy.

In Figure 3 we have plotted the integrated flux from 1625 Å to 1675 Å for 22 Vul as a function of absolute phase for both ingress and egress. The new points not taken from PAH have been circled. It is clear that the addition of these new points strongly confirms PAH's conclusion that the atmospheric eclipse is asymmetric in 22 Vul.

Comparing Figures 2 and 3 it is clear that the eclipse in 22 Vul begins symmetrically but departs from symmetry at a phase greater than about 0.05. Further, the pronounced dip at ingress is suggestive of some sort of feature in the chromosphere. PAH suggested a gas stream to the hot component or clumps in the atmosphere (perhaps related to magnetic fields). The asymmetries observed in the optical observations of zeta Aur were, by contrast, attributed to the effects of the

TABLE 1

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Figure 3. Integrated 22 Vul flux in wavelength range 1625 Å to 1675 Å in units of 10^-12 ergs/s/cm² plotted against absolute phase. Circled points are from present research, other points from PAH.
ionization front due to the B star on the rotating chromosphere of the supergiant (Ref. 6).

It is of interest that the feature first reported visible during the August, 1984 ingress of 22 Vul is still visible during the April, 1985 ingress. Unless the system is co-rotating, this fact renders suspect the hypothesis that a single stationary clump in the chromosphere accounts for the absorption in both cycles. Co-rotation (requiring a rotational velocity of the primary of order 10 km/s) would seem inconsistent with the rotational velocity which we have previously derived for the primary, viz., $2.4 \pm 2.5$ km/s (Ref. 5).

All our statements are preliminary. 22 Vul should be examined thoroughly during a single eclipse in order to ascertain whether the asymmetry is really a permanent feature. In the case of zeta Aur the coverage at ingress should be extended further from eclipse.

4. ACKNOWLEDGEMENTS

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5. REFERENCES


SUPERIONIZED PLASMAS IN ALGOL BINARIES

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ABSTRACT

Of the three types of circumstellar material in interacting binary stars (mass-transferring stream, accretion disk, and outflowing gas), the third type is studied for semidetached binaries of the Algol type. A survey of 11 systems observed during the total primary eclipse shows that the same type of emission-line spectrum appears, but that important differences exist. They seem to correlate with the character of the mass-accreting star, although it is not clear if the correlation is with spectral type or with mass. The line emitting plasma is no doubt specified, but the dominant electron temperature varies from system to system and determines the relative line strengths. Evidence for CNO processing, affecting the abundance ratios C/N, is also present in some systems.

Keywords: Interacting binaries, Semidetached binaries, Algols, ultraviolet spectra, superionized plasma, stellar wind, abundance anomalies.

1. THREE FACES OF CIRCUMSTELLAR MATTER

Circumstellar matter in binary systems poses about the same problems and challenges like interstellar matter. Interstellar matter in the Galaxy is bad nuisance to many investigators of stars and galaxies, a fascinating subject to some, and an important part of the evolutionary cycle from a broader point of view. In much the same vein, circumstellar matter in binary stars is a formidable obstacle if we want to determine the pure characteristics of the component stars; understanding its structure and physics is a challenging enterprise to some of us; and its role in the evolution of the interacting binary systems forces every investigator of binary stars and of stellar evolution to take its presence very seriously.

The evolutionary role of circumstellar matter in interacting binary systems is different from that of the interstellar matter in the Galaxy. The circumstellar matter does not coalesce into stars; in fact, it is rather a product of the dismantling of one of them, although it contributes to the growth of the other. Yet perhaps even more important is that part of the circumstellar matter that carries matter and angular momentum away from the system, thereby contributing to the interstellar medium.

Thus the concept of the three faces of the circumstellar matter in binary stars reappears in a new shape when we consider its evolutionary role: we can distinguish the mass-transferring stream that dismantles the "loser"; the accretion disk that adds mass onto the "gainer"; and then there should exist something akin to a stellar wind that carries gas away from the system.

The third component of circumstellar matter appears to me the most exciting and challenging structure, because it is the most elusive part. The first model sequences describing the evolution of binary stars undergoing mass transfer assumed a purely conservative case, namely only redistribution of mass and of orbital angular momentum between the two components, with no losses from the system, although already in 1967, Paczynski and Ziolkowski (Ref. 1) realized that this assumption is too constraining. The first systematic attempt at a comparison of theoretical models with actually observed systems (Ref. 2) confirmed this suspicion and since that time, every such study has pointed out to the necessity of assuming a substantial loss of mass and angular momentum from the binary system (Ref. 3).

The evolutionary models, dealing with the component stars, do not tell us how this mass loss occurs, and only vaguely indicate that it is, naturally, more likely to occur during the rapid phase of mass transfer. So far, observational evidence has been equally mute. In fact, we are far from a clear understanding how the observed structures relate to the three expected components: stream, accretion disk, and outflowing wind. The various segments of streams that Otto Struve sketched in the 1940's seem to be partly the mass-transferring stream and partly perhaps segments of an accretion disk. The rotating ring introduced by A. H. Joy and seen as double-peaked Balmer emission lines may be the optically thin edge of an accretion disk. The "circumstellar shell" or "circumstellar envelope", occurring both in interacting binary stars and in Be stars, the main source of the nuisance mentioned above, is a much more obscure structure, although it ought to be, in all probability, related to some kind of accretion disk or its extended atmosphere. It is obvious that much work is yet to be done by those who consider the circumstellar matter to be a fascinating subject by its mere presence. Where, in this scheme of things, is the component that carries the gas away from the system?
2. SUPERIONIZED PLASMAS

One possible vehicle carrying gas out of the system was identified by Kondo, McCluskey, and Harvel (Ref. 4) in U Cephei. It is a stream, apparently carrying mass from the loser, going around the trailing hemisphere of the gainer, which seems to be (at least in part) deflected near the L3 point and flows away from the system. A dynamical study will be necessary to supplement the spectroscopic observations of this feature, since they are, of necessity, fragmentary.

The most promising component of the circumstellar matter, as far as mass loss from the system is concerned, is, in my opinion, the superionized plasma manifested by the presence of strong ultraviolet emission lines, as shown in Figure 1. The same lines were observed in absorption in U Cephei by Kondo, McCluskey, and Stencel (Ref. 5) and then in several other Algol systems by Peters and Polidan (Ref. 6). I will discuss here their appearance as emission lines, because I have studied them systematically over the past ten years, and because the plasma appears in a purer form when observed in emission. By that I mean that the severe problem of blending with a cooler circumstellar shell and with photospheric absorptions disappears, and so does the possibility of partial contamination of absorption lines by emission, which bothers so much Sahade (Ref. 7).

The discovery of emission lines of N V, Si IV, and C IV in the spectra of non-degenerate interacting systems came as a real surprise, since the stars in these systems are too cool to photoionize the plasma. The opinion which seems to be held by Sahade (Ref. 8) that, after all, the hot plasma could have been anticipated, seems to read too much into the smart remarks by Popper and by Smak made in 1972 (Ref. 9) that there is evidence for a non-stellar source of energy in circumstellar rings. From optical observations, one could hardly anticipate the existence of regions at an electron temperature exceeding 100,000 K. When this plasma was discovered with Copernicus in β Lyrae, it was considered as a unique phenomenon in a uniquely bizarre interacting system. Only when I and R. H. Koch found, in 1978 (Ref. 10), that a group of bizarre eclipsing systems (the W Serpentis stars) shares the ultraviolet characteristics of β Lyrae did it become clear that we are dealing with a more widespread phenomenon.

The difficulty with the W Serpentis systems is that the component stars are so deeply embedded in the other structures of the circumstellar matter that it is very hard to recognize the basic structure of the system, that is, its size, masses and spectral types of the component stars, etc. Without these fundamental data it is impossible to evaluate the power emitted by the emission lines and other necessary parameters. Therefore, I decided to start a systematic study of the Algol systems on the assumption that they probably differ from the W Serpentis stars only by a smaller rate of mass transfer. The emission lines of the superionized plasmas observed in ordinary Algols are indeed so much weaker than in the Serpentis that only spectra taken during the total eclipse of the hotter star
reveals them. So far, I have been able to detect emission lines of this type in 11 ordinary Algols, namely S Cnc, U Cep, RS Cap, RY Gen, TY Bva, UX Xon, RY Per, U Sge, V356 Sgr, RW Tau, and S Vel. Only one failure to see them in a total eclipse occurred, for W Del, and once in two eclipses the lines were found to be extremely faint in RW Tau, in accord with the well-known fluctuation in the strength of the Balmer emissions (Ref. 11).

My effort, strongly affected by the fluctuating attitudes of the IUE peer review committees, has been to cover a wide range of Algols, in particular as to the masses and spectral types of the gainers. This is no easy task, since the Algols tend to prefer spectral types of the primaries between B8 and A0; this clustering is actually stronger than it appears in the statistics, since some systems classified as A1 through A5 are actually late B. As one progresses from B7 to earlier types, Algols become rare. Yet it is important to persist in this survey, as I hope the reader will agree when he inspects Figures 1 and 2.

The star TT Hydræ, in Fig. 1, represents the later type Algols, since its primary is B9.6 V (Ref. 12). Note that the dominant emission line is either Si IV or C IV, depending on whether you consider both doublet components together or separately. In any case, N V is very much weaker than either C IV or Si IV. This is, at least in part, an effect of a relatively low representative electron temperature of the plasma (although it is most likely stratified and a portion of it may be at a temperature higher than 100,000 K). The relatively low "mean" or "representative" electron temperature is indicated by the fairly large strength of the Si II resonance lines, by the greater strength of Al II compared to Al III, and by the weakness of the Fe III (34) trio at 1895, 1914, and 1926 A. The weakness of Fe III is more clearly seen in comparison with the broad blends of Fe II and other metallic singly-ionized lines seen in the LWP camera (Ref. 12).

In contrast to the emission spectrum in TT Hydræ stands the spectrum obtained during the total primary eclipse of RY Persei, shown in Figure 2. This star is usually classified as B5 as far as the gainer is concerned, and although there are some doubts about the spectral class, it is no doubt earlier than TT Hydræ. While the basic character of the emission spectrum is preserved, some differences are rather striking. In the first place, C IV is completely dwarfed by Si IV and, more importantly, by N V. The general degree of ionization is no doubt higher; Al II is almost negligible compared to Al III, Si II is also very weak (the broad blend at 1300 A seems to be mainly due to Si III), Fe III is
strong, while there are no Fe II lines seen in the LWP camera spectrum.

It would seem that there is a strong correlation between the dominant level of electron temperature and the effective temperature of the hotter star. However, the ionization and excitation of the plasma is certainly maintained collisionally, and the required energy is in some way derived from the potential energy of the impacting material coming from the loser. It is an interesting problem to decide if the higher effective temperature of the gainer plays any role at all. A gainer's higher effective temperature goes hand in hand with its larger mass, therefore higher potential energy of infall under otherwise equal circumstances.

The ratio of intensities of the N V and C IV lines is no doubt affected by the electron temperature of the plasma, but it is equally certain that elemental abundances play an important role as well. For β Lyrae, Balachandran et al. (Ref. 13) have shown that the material now observed in the photospheric spectrum of the loser was in the past processed by the CNO bi-cycle inside the loser, as a consequence the atmosphere of the loser is richer in He, poorer in hydrogen, richer in N and poorer in C. The UV resonance emission lines show this effect as well: as in NY Psereli, N V is a stronger line than C IV. A very extreme case of the same phenomenon is seen in V356 Sagittarii, in which N V is strong while the carbon lines are well-nigh absent. While the electron temperature certainly plays an important role in this system with the gainer even earlier than in NY Psereli, abundance effects cannot be denied.

That the relation between the type of the gainer and the representative electron temperature of the hot plasma is probably not a simple correlation to effective temperature of the gainer is obvious from the spectrum of the W Serpentis star RX Cas (Ref. 14). One would judge the emission line spectrum to be intermediate between that of TT Hydrae and NY Psereli, since the lines of N V and C IV are about equally strong. However, we have not found in the spectrum of RX Cas any evidence of a star earlier than late F or early G. It is conceivable, however, that an earlier-type star in hidden in an optically thick disk that simulates an F-G star.

3. TOTAL POWERS EMITTED

The relative line strengths are at most affected by an occasional uncertainty as to the amount of interstellar reddening, and usually not too seriously. Evaluating the total emitted powers is more difficult, since uncertainties in distances enter seriously. At the moment, the W Serpentis stars are disqualified except for β Lyrae (Ref. 15) and SX Cas (Ref. 16). If only the strongest lines are included (in order to avoid problems with a potential continuum), then by far the most powerful emitter is β Lyrae, then comes V356 Sgr (which is in many respects similar to β Lyrae). Next comes SX Cas and not far behind is NY Psereli. Much less power is emitted by the emission lines in RS Cep and TT Hya, and still less by NY Gem, U Cep, S Cnc, and last comes U Sagittae. Here again, there may be more than one parameter at play. Even if the mass loss rate were the only decisive variable, it depends on the initial thermal evolutionary scale of the loser as well as on the phase of the mass transfer process.

4. REFERENCES

ABSTRACT

Various characteristics are compared and summarized for a group of composite spectrum stars which have strong H alpha emission and peculiar satellite UV spectra. Spectroscopic periods and photometric variability are now defined for most of these systems. Compared with "normal" non-interacting composite spectrum binaries, they exhibit excess flux in the middle UV region. This is believed to indicate the presence of an accretion disk.

Several other binary star systems with similar optical properties (a luminous F star with a B or Be companion and strong H-alpha emission) have been found to display related, though less extreme, complexity and variability in their satellite-UV spectra. Optical radial velocities have recently determined or refined their orbital periods. Photometric studies reveal some degree of optical flux variability, with a signature of ellipsoidal tidal distortion. Compared with synthesized flux distributions of pairs of "normal" stars, these systems have excess flux in the mid-UV region. Several properties of the systems as now known are summarized in the table: ground-based spectral classification, IUE far-UV spectral classification, period from radial velocities, optical photometric variability (range observed), presence of mid-UV flux excess (range observed), and general nature of far-UV variability (range observed).

2. GROUND-BASED SPECTROSCOPY

All objects in the table were noted in early Mt. Wilson work as having prominent H alpha emission. We have been observing most of these systems for several seasons in the red spectral region, and find Be-star type H alpha emission profiles which vary both in total emission strength and in V/R component ratio. In all five systems scans of the 5900A region display double Na D absorption. Due to the constancy in radial velocity and strength of the deep, narrow line component it is believed that this component is formed in a circumstellar cloud. A near infrared scan of HD 166612 shows Paschen line emission and very strong Ca II triplet emission.

3. IUE SPECTROSCOPY

SWP spectra of early type stars even at low dispersion provide sensitive diagnostics for photospheric temperature and for circumstellar material. For dozens of composite spectrum binaries Parsons and Ake (Ref. 7) have successfully classified the hot components relative to standard IUE spectra. The systems in table 1 show B-type hot components but exhibit UV peculiarities ranging from mild to strong enhancements of Si IV and C IV stellar wind features to very complex absorption features due to warm ions such as Fe II. All of the peculiar features have been found to vary during the 4 years of our IUE observing programs.
Figure 1. Comparison of observed and synthetic energy distributions from the far UV to near IR for some P + Be binaries. Observed IUE fluxes are expressed as magnitudes (squares and diamonds, for higher and lower reliability), along with Johnson UBVRI photometry converted to the same energy scale. Best-fitting synthetic combinations of single-star intrinsic colors are shown by plus (+) signs, while the component distributions are plotted as curves and labelled with their corresponding spectral types (luminosity classes are assumed, not derived). The 2200À dip is modelled with a standard interstellar extinction curve and parameterized by $E = E(B-V)$. The differences $O-C$ are plotted as asterisks (*) at the bottom of each panel to the same magnitude scale. In almost every case a mid-UV flux excess is apparent.
the I' + He systems, however, there is little correspondence in the nature of the profiles. Stellar wind components are generally apparent: HD 127208 has the highest velocity wind at about 1800 km/s. The great strength of the emission in some systems may be due to tidals, as suggested by Ciebelski and Stanekowski (Ref. 3).

4. SPECTROSCOPIC RESULTS

With the exception of HD 166612, which does not yet have adequate observational coverage, the system display regular periodic variation in radial velocity of the cool component’s absorption lines. Our ground-based spectroscopy plus many observations of HD 207739 by Griffin (private communication) have allowed us to determine the orbits using standard techniques. These are all nearly circular with amplitudes of 70-80 km/s, indicating that rather massive systems are involved.

5. OPTICAL PHOTOMETRY

Photometric programs by us, Fernandes (Ref. 2), and especially Cherepashchuk (Ref. 1), have demonstrated clear ellipsoidal variability of HD 207739. With its 151 day orbital period the primary must be considerably larger and more luminous than implied by its spectral type, F8 I. In order to be so totally distorted, we are acquiring UV photometry on the other systems, some of which now have enough data to show the ellipsoidal signature of a star filling much of its Roche volume.

6. H$eta$ SPECTROPHOTOMETRY

Blind lines from SD and LSR (corrected for sensitivity degradation) images are being analyzed with the composite energy distribution tool described by Parsons (Ref. 6). The analysis of most ESP data is pending reprocessing with the improved H$eta$. The analysis tool has been used successfully by Parsons and Ake (Ref. 7) on large numbers of non-interacting cool plus hot binaries. Almost every observation of the F + Be systems, however, cannot be matched by a combination of two normal stellar energy distributions and a standard interstellar extinction curve. There is a broad excess in observed flux from about 2000 A to the F magnitude, apparently peaking around 2900 A. Similar UV excesses are calculated to originate from the inner boundary layers of accretion disks around F start (Ref. 9).

In HD 207739, the far-UV flux varies dramatically with an observed range of 1.2 magnitudes in the 1500A region. There is no clear correlation with phase; unfortunately, very few data have been taken within the same orbital cycle. There is a succession of partial eclipses: the flux was relatively low right at the time at which the F star was in front of the hot object, but it may be coincidental since high flux levels have been seen in other cycles within a few days of conjunction.

7. SUMMARY

The emission lines, mid-UV flux excess, tidal distortion, and erratic variability in flux and line features of the systems studied here suggest that these binaries are in a stage of mass transfer from a yellow giant or supergiant star to a hot dwarf star with a substantial accretion disk as well as circumsystem material.

8. REFERENCES

ABSTRACT

Far ultraviolet spectra of WZ Sge from July 1979 through November 1981 were studied to search for the spectroscopic signature of the white dwarf primary. The ultraviolet fluxes continued to decline throughout this period. The observed energy distribution in Nov 1981 can be matched by a DA-type white dwarf with an effective temperature of 14500°K and an apparent visual magnitude of 14.7. Questions still remain about whether the white dwarf actually has been seen in this system.

keywords: cataclysmic variables, white dwarfs, ultraviolet spectroscopy.

1. INTRODUCTION

WZ Sagittae is a dwarf nova whose outbursts are very infrequent (1913, 1946, and 1978) and of large amplitude. During quiescence it is near V=15.2 (Ref. 1) and it peaked in outburst at V=7.8 (Ref. 2) on 1978 Dec 1/2. Its distance has been measured to be about 83 pc (Ref. 3).

Greenstein (Ref. 4) observed broad Balmer absorption lines during quiescence and interpreted them as being photospheric lines from the white dwarf. In contrast to this, Robinson, Nather, and Patterson (Ref. 5) concluded that these absorption lines arise in the accretion disk and that the white dwarf is considerably fainter than the disk in visual light. To attempt to resolve this disagreement, I examined the IUE spectra obtained as WZ Sge returned to quiescence for indications of the white dwarf primary.

2. OBSERVATIONS

IUE spectra of WZ Sge were obtained on 1979 July 7, 1979 July 11, 1980 April 25, 1980 Dec 25 (Short Wavelength Prime only), 1980 Dec 27, and 1981 Nov 23. Target acquisitions for these observations were done by blind offset from nearby stars. Because of the blind offset, no magnitudes are available from the Fine Error Sensor (FES). Furthermore, the wavelength assignments are subject to errors in the specified coordinates and in IUE's slewing accuracy. Other observations were attempted on 1979 Oct 23 and 1981 April 15 with target acquisition by centering on the light detected with the FES. These observations were greatly underexposed and useless to this investigation. It is thought that the cause of these failures is a V=14.27, cool star which was unknown to the observers and only 7 arcsec from the target (Ref. 6). Since this companion is brighter in the visual than the variable, the aperture would have been centered on the companion and most of the light from WZ Sge would have missed the aperture. Photometry of the companion (Ref. 6) indicates it is very faint in the ultraviolet and unlikely to contaminate any of the observations reported here.

The observations were reduced using techniques described by Holm et al. (Ref. 7). Figure 1 shows the spectra in the 1200-2000A range. A sample of the energy distributions during outburst and during the post-outburst decline are shown in Figure 2. Holm et al. (Ref. 8) found that E(B-V)=0.025. Therefore, no extinction correction has been applied to these data. It is clear from both figures that this cataclysmic variable continued to fade and to cool throughout this period.

Fig 1. Spectra of WZ Sge during the return to minimum.
3. THE SPECTRUM

Strong absorption features persisted while the peak flux decreased from about 2.0x10^{-13} ergs/cm^2/s/A to 6.0x10^{-14} ergs/cm^2/s/A and the wavelength of the peak flux increased from 1300Å to 1500Å. Apparently the same features are seen during outburst when the fluxes are about 100 times greater. They are tentatively identified as Si II mult. 4 at 1262Å, Si III mult. 4 and Si II mult. 3 near 1300Å, C II mult. 1 at 1335Å, Si IV mult. 1 at 1400Å, Si II mult. 2 at 1530Å, and Al III mult. 1 at 1860Å. The strength of these features is given in Table 1. The N V mult. 1 at 1240Å may be seen in some of the spectra but is weak. C IV mult. 1 at 1550Å appears primarily as a broad emission feature with central absorption. The Si II 1530Å feature gives C IV the appearance of having high velocity, blue shifted absorption.

These line identifications are somewhat uncertain both because of the wavelength errors introduced by the blind offset and because of the low resolution of these spectra. The wavelength errors cannot be too bad because cross correlation of these spectra with spectra obtained in outburst shows shift of less than 4Å. Furthermore, during outburst the identified ions appear in a high resolution spectrum, SWP 3567, that was obtained on 1978 Dec 10. Thus there is some evidence for the identifications. Nonetheless, with low resolution spectra it is not possible to show that none of the features seen during outburst are replaced by other features that are near the same wavelength. For example, the Si IV absorption at 1400Å could be replaced or supplemented by absorption from the hydrogen ion quasi molecule (Ref. 9, Ref. 10) without indication in these observations.

4. RESULTS

If the white dwarf is visible in the far ultra-violet, the observed energy distribution must agree with that of a white dwarf. To determine if this minimum criterion could be met, the energy distribution of WZ Sge on 1981 Nov 23 was compared with the observed energy distributions of DA-type white dwarfs, DB-type white dwarfs, main sequence stars, Planck functions, and power laws to determine whether any match could be found.

Only DA-type white dwarfs gave a reasonable fit. Ignoring the absorption lines discussed above, I found that Gl16-52, T_{eff}=14,500°K (Ref. 11), agrees well with WZ Sge on 1980 Nov 23, as shown in Figure 3. This is encouraging.

However, it turns out that the earlier and brighter observations also can be modeled by a white dwarf energy distribution. In particular, Glw+73°[03I, T_{eff}=15,400°K (Ref. 11), gave good agreement with WZ Sge on 1980 Apr 25, as shown in Figure 4. Thus it is possible to match the energy distribution of WZ Sge on two different dates with DA-type white dwarfs with different temperatures. It appears that either we are not seeing the white dwarf but an accretion disk that mimics a DA-type energy distribution or the effective temperature of the white dwarf varied during the sequence of observations. Perhaps the white dwarf was heated by radiation from the disk during the outburst, e.g. Williams et al. (Ref. 12), and we are seeing a post-outburst cooling of the primary.

If the agreements with the white dwarf energy distribution extend into the visual, WZ Sge would
SEARCHING FOR THE WHITE DWARF IN WZ SAGITTAE

have had V=14.62 on 1980 Apr 25 and V=14.68 on 1981 Nov 23. Unfortunately I do not have any visual photometry with which to test these predictions, but both predictions are much brighter than Walker (Ref. 1) found at minimum. It does not look good for the white dwarf hypothesis if the candidate white dwarf is significantly brighter in the visual than the quiescent system, which must include contributions from both the accretion disk and the primary star. Since Walker's photometry was obtained longer after outburst than the IUE observations, perhaps this apparent discrepancy can be resolved if WZ Sge had not yet reached quiescence in Nov 1981.

More questions are raised by the absorption features discussed above. They might be caused by heavy elements accreted onto the primary, but why don't they change significantly between 1979 Jan 1 and 1981 Nov 23 while the luminosity decreases by a factor of about 10? If the features arise in the accretion disk when the system is bright, then the absence of significant change in line strengths when the system returns to quiescence suggests that they arise in the accretion disk at minimum also and the disk must be bright compared with the white dwarf. On the other hand, one might argue that on 1979 Jan 1 we observed a white dwarf that was 10 times more luminous than on 1981 Nov 23 because it had been heated by the outburst and that the absorption features came from the white dwarf throughout the decline. However, then the effective temperature would have been about 1.8 times hotter in Jan 1979 than in Nov 1981. The lack of line strength change argues against such a temperature change.

5. CONCLUSION

The ultraviolet spectrum of WZ Sge near minimum is not completely consistent with the hypothesis that the white dwarf is visible, although the ultraviolet energy distribution can be matched by a DA-type white dwarf. This does not explain the behavior of the absorption spectrum. However, the accretion on the top of the atmosphere of material having normal metal abundances might greatly alter the appearance of the spectrum. Development of model atmospheres having solar abundances for white dwarfs is recommended to investigate this possibility. Models of white dwarfs heated by a bright accretion disk are also needed to determine whether this mechanism could cause the surface temperature to be high for several years after the outburst.

6. REFERENCES

Model Chromosphere and Transition Region for 56 Peg (K0 IIp + wd): A Preliminary Study

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Abstract
Observations of 56 Peg (K0 IIp + wd) have shown the presence of ultraviolet emission lines associated with warm (10^5 K) material. It has been suggested that this emission comes from an ionized region in a cool wind around the secondary. The characteristics of the emission, however, support the view that the lines are formed in a transition region around the late-type supergiant. A self-consistent model chromosphere and transition region are presented here as further evidence. A satisfactory model, taking into account the transition region material, the variable asymmetry in Mg II and the X-ray emission might be possible in terms of a hybrid supergiant with an X-ray illuminated cool wind.

1 Introduction
56 Peg is a mild barium star, thought to have a white dwarf companion, that shows the presence of large amounts of hot gas in its ultraviolet spectrum. The C IV (1550 Å) emission and other transition region-type lines observed in its IUE spectra are far more intense than expected for a giant of its spectral class, K0 II. The fraction of C IV emission to bolometric luminosity detected is 80 times greater than that observed for a TrA, a K4 hybrid giant (Simon, Linsky and Stencel, 1982), whilst its X-ray luminosity of about 30 x 10^{30} ergs s^{-1} (Schindler et al., 1982) is at least an order of magnitude greater than those of the Hyades K0 giants which are also thought to be members of wide binary systems (Balinnas et al., 1983). It has also been observed to have variable asymmetry in its MgII k line, perhaps evidence for a rotational period of about four years (Stencel et al., 1984).

The presence of a companion is clearly indicated by the excess continuum emission in its ultraviolet spectrum, shortward of 2000 Å. This was first interpreted as being from the surface of the white dwarf companion (Schindler et al., 1982), but it was subsequently argued that the emission came from an accretion disc about the companion, formed from gas captured from the stellar wind of the giant (Dominy and Lambert, 1983). Wind accretion can also account for the observed X-ray flux, given the uncertainties in both the expected wind mass-loss rate, and the efficiency of the accretion process. Schindler et al. (1982) also proposed that the observed C IV flux, and the flux from other lines indicating the presence of warm, 10^5 K material, arises as a result of an accretion energy source; emission from the disc itself, or, more likely, from an X-ray illuminated wind, being responsible.

Despite the evidence for a companion and activity arising from accretion, it is remarkable that the atmosphere of the giant can be modelled with a transition region and hot corona, using conventional techniques. An initial study was carried out by Jordan et al. (1982). Further evidence for an atmospheric structure that would be considered relatively normal in a giant of earlier spectral type comes from the correlations between various chromospheric and transition region lines that 56 Peg is known to satisfy (Oranje, 1986). The X-ray flux detected also fits the expected relation between Mg II and X-ray emission (Rutten, 1987).

This paper addresses these issues. In the first two sections the IUE observations are used to construct a model of its atmosphere with a transition region and hot corona. The next section discusses the development of a chromospheric model consistent with the transition region model. The final section is more speculative. The energy balance of the model transition region and corona is discussed. The observed losses give some indication of the energy input required to maintain a state of equilibrium. The dissipation of Alfvén waves in the magnetic structures in late-type stellar atmospheres is known to be able to create hot coronae and hence to induce transition regions (Hartmann and MacGregor, 1980). The static model discussed here is only a first approximation, and it is hoped that a proper treatment of X-ray illuminated cool winds will give additional insights into the structure of the atmosphere of 56 Peg.

2 Observations
The IUE high dispersion spectra used have already been discussed by Jordan et al. (1982). The very long (1040
minute) exposure, high resolution, short-wavelength spectrum, SWP 18283, was re-extracted and re-calibrated using the absolute flux calibrations of Bohlin and Holm (1980) (low resolution) and the high resolution, low resolution ratios of Cassatella et al. (1981). The adopted stellar parameters in Table 1 were used to obtain the fluxes given in Table 2.

The fluxes and widths were measured by fitting gaussians, triangular peaks, or by hand, as seemed appropriate.

### Table 1: Adopted Parameters of 56 Peg (K0 IIp + wd)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>215 pc</td>
<td>1</td>
</tr>
<tr>
<td>$T_{\text{eff}}$</td>
<td>4500 K</td>
<td>2</td>
</tr>
<tr>
<td>$y_0$</td>
<td>25 cm$^2$s$^{-1}$</td>
<td>2</td>
</tr>
<tr>
<td>$\delta'$</td>
<td>2.6 x 10$^{-3}$</td>
<td>3</td>
</tr>
</tbody>
</table>


Due regard was given to hot spots, reseau marks and noise visible on the accompanying photowrite. Table 2 also gives the stellar fluxes corrected for interstellar absorption, assuming $E(B-V) = 0.1$. The extinction curve of Savage and Mathis (1979) was used, increasing the ratio of C IV (1555 Å) to Mg II (2800 Å) by nearly 35%. $E(B-V) = 0.1$ is consistent with the hydrogen column density of $5 \times 10^{20}$ cm$^{-2}$ required to account for the Ly$\alpha$ interstellar absorption feature at the expected temperature (Bohlin et al., 1978).

### Table 2: UV Emission Line Fluxes

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$ (Å)</th>
<th>$F_\text{i}$ (ergs cm$^{-2}$ s$^{-1}$)</th>
<th>$F_\text{i}$ (corrected) (ergs cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N V</td>
<td>1240</td>
<td>1.5 (4)</td>
<td>3.6 (4)</td>
</tr>
<tr>
<td>C IV</td>
<td>1550</td>
<td>3.1 (4)</td>
<td>6.5 (4)</td>
</tr>
<tr>
<td>Si IV</td>
<td>1402</td>
<td>1.4 (4)</td>
<td>3.0 (4)</td>
</tr>
<tr>
<td>C III</td>
<td>1892</td>
<td>1.4 (4)</td>
<td>3.4 (4)</td>
</tr>
<tr>
<td>C II</td>
<td>1335</td>
<td>1.8 (4)</td>
<td>4.1 (4)</td>
</tr>
<tr>
<td>Si II</td>
<td>1808</td>
<td>2.9 (4)</td>
<td>5.8 (4)</td>
</tr>
<tr>
<td>Mg II</td>
<td>2800</td>
<td>1.2 (6)</td>
<td>1.8 (6)</td>
</tr>
</tbody>
</table>

### Model transition region

The line flux for an effectively thin emission line is given by

$$F_{ij} = \frac{6.8 \times 10^{-22} N \omega_i \omega_j}{\lambda} \int N_e^2 G(T_e) dh,$$

where

$$G_{ij}(T_e) = \frac{N_{\text{tot}} N_i}{N_e^{-1/2} \Delta E} \Delta \omega / \Delta T$$

is the contribution function of the line, assuming that collisional excitation and radiative de-excitation dominate in the region of line formation (Jordan and Brown, 1981). $\Omega$ is the collision strength, $N_e/N_H$, the elemental abundance, $\omega$ the statistical weight of the lower level, $\lambda$ the wavelength, $\Delta E$ the excitation energy, $N_{\text{tot}}/N_e$ the relative ion abundance and $N_i/N_{\text{tot}}$ the fractional population of the lower level. Changing the variable of integration to $T_e$ in (1), defining

$$f(T_e) = N_e^2 \frac{dh}{dT_e}$$

and naming the constant in front of the integral $M_{ij}$, gives

$$F_{ij} = M_{ij} \int f(T_e) G_{ij}(T_e) dT_e$$

for each transition $i \rightarrow j$. This set of integral equations can be solved for $f(T_e)$ by assuming a functional form for $f(T_e)$ and requiring that it be smooth and non-negative. Note that the usual emission measure $Em(0.3)$ is given by

$$Em(0.3) = \int_0^{T_f} f(T_e) dT_e,$$

where $\log T_f - \log T_i = 0.3$.

To model the transition region and corona we assume hydrostatic equilibrium,

$$\frac{dP_e}{dh} = -7.1 \times 10^{-5} P_e g_e / T_e$$

and an equation of state,

$$P_e = N_e T_e.$$

Combining (3), (6) and (7), and integrating, gives

$$P_e = P_0 + 1.4 \times 10^{-8} \int_0^{P_0} T_e f(T_e) dT_e,$$

where $P_0$ is the known pressure at temperature $T_0$. Two models for the atmosphere of 56 Peg are shown in Figure 1. Model 1 has $P_0 = 0$ at $log T_0 = 5.5$ whilst Model 2 is integrated down from the coronal temperature and pressure deduced from the X-ray measurements. Both models reproduce the fluxes in the permitted transitions to within better than 20% and the C III 1909 Å transition to within 45%. Model 2 also accounts for the Si III 1892 Å line flux assuming that it is formed by collisional excitation and radiative de-excitation. This confirms that the line is formed in the lower density limit, $N_e \leq 10^{10}$. The electron density of $10^{10}$ cm$^{-3}$ at $log T_e = 4.1$ in Model 2 also agrees with the density deduced from the line ratios of fluxes in the C II 2325 Å lines (Lennon et al., 1985).

It is possible to interpret the widths of the optically thin lines as an indication of turbulence in the atmosphere, which might then be expected to provide turbulent support and which must be taken into account in the equation of hydrostatic equilibrium. This has the effect of reducing the gravity in equations (6) and (8). The new 'effective' gravity
Model 2.

Model 1.

Figure 1: Transition region models.

is given by

\[ g_{\text{eff}} = g_e (1 + \rho V^2_{\text{rad}} / 2P_r)^{-1} \]  \hspace{1cm} (9)

The ratio of \( g_e \) to \( g_{\text{eff}} \) is nearly constant throughout the transition region of 56 Peg. Models constructed using the effective gravity are similar in structure to Model 2, but have a transition region that is shifted outwards in height from the surface of the star by a factor of 3.

4 Initial chromospheric model

The transition region modelling described above is really only appropriate for temperatures above \( 2 \times 10^4 \) K. Below this temperature the state of ionization of hydrogen is changing rapidly and the important diagnostic lines are no longer effectively optically thin; more sophisticated radiative transfer calculations must be performed. The development of semi-empirical chromospheric models has been described by Basri et al. (1981). A slightly different procedure was followed in this case to derive a preliminary model of the chromosphere of 56 Peg. The mass column density at the base of the transition region, \( m_0 \), was taken from the transition region model in the previous section, whilst the minimum temperature, \( T_{\text{min}} \), and the corresponding value of the mass column density, \( m(T_{\text{min}}) \), were found, in the first approximation, from the Ca II H and K line wings in the complete redistribution limit (Ayres and Linsky, 1975). The radiative transfer program, MULTI, was used to produce a hydrostatic equilibrium model using a four level hydrogen atom (Carlsson, 1986). The Lyman continuum was treated in detail, but the Paschen and Balmer continua were modelled by fixed radiation temperatures. The results are given in Table 3. This model was able to reproduce the fluxes observed in Mg II \( f \) and \( k \) (again using MULTI, with a 5 level atom), in both complete and partial redistribution. The partial redistribution profiles, however, were a factor of five narrower than those of the observed emission. It has already been pointed out in the literature that the Wilson-Bappu magnitude derived from the Mg II \( k \) line disagrees by some four magnitudes from the adopted absolute magnitude (Mullan and Stencel, 1982). It is clear that further insight into the geometry and kinematics of the line formation region is required in order to explain both the width of the observed profile as well as its variable asymmetry.

\[
\begin{array}{cccc}
\text{m}(\text{g cm}^{-2}) & \text{T} (\text{K}) & \text{N}_e(\text{cm}^{-2}) & b_1 & b_2 \\
1. & -3.45 & 16000 & 2.0(9) & 8.1(7) & 8.8(6) \\
2. & -3.13 & 10000 & 5.0(9) & 1.1(4) & 1.3(4) \\
3. & -3.1 & 9000 & 4.2(9) & 4.4(3) & 4.6(3) \\
4. & -3.0 & 7000 & 3.1(9) & 2.2(3) & 2.3(3) \\
5. & -2.5 & 7000 & 3.0(9) & 8.4(2) & 8.5(2) \\
6. & -2.0 & 6000 & 2.0(9) & 2.2(2) & 2.2(2) \\
7. & -1.5 & 5100 & 7.0(8) & 5.3(1) & 6.0(1) \\
8. & -1.0 & 4000 & 4.3(8) & 5.2(0) & 7.5(0) \\
9. & -0.5 & 3450 & 7.5(8) & 1.9(0) & 1.9(0) \\
10. & 0.0 & 3400 & 1.7(9) & 8.5(-1) & 8.5(-1) \\
11. & 1.0 & 3620 & 1.9(10) & 9.8(-1) & 9.8(-1) \\
12. & 2.0 & 3660 & 9.3(10) & 1.0(0) & 1.0(0) \\
\end{array}
\]

Table 3: Adopted Chromospheric Model

5 Energy balance

The radiative flux losses in a region \( \log T = \pm 0.15 \), a typical range for the formation of an emission line, are given by

\[ \Delta F_r \approx 0.8 \rho m(0.3) P_{\text{rad}} \]  \hspace{1cm} (10)

provided \( P_{\text{rad}} \), the power loss function, does not vary too much over the line forming region (Jordan and Brown, 1981). The summed losses, from the high temperature downward, are shown in Figure 2. If we assume, for the time being, that flows or winds are not important, then in the corona the radiative flux losses must be balanced by non-thermal heating.

A magnetic field of the order of 10 gauss, indicated by the observed line widths, assuming that \( \rho(V_T) = \langle B^2 \rangle / 8\pi \) and \( B^3 \geq 4 \langle B^2 \rangle \), (12)

and a wave flux of \( 10^7 \) ergs cm\(^{-2}\) s\(^{-1}\) at \( \log T = 4.7 \) would be consistent with the observed radiative losses provided that the wave was damped over the emission region.

\[
\begin{array}{cccc}
\text{Model 2.} & \text{Model 1.} \\
\end{array}
\]

Figure 2: Radiative Power Loss (summed downwards from the high temperatures).
6 Conclusion and Discussion

The models developed here have shown that it is possible to explain the emission observed in the IUE spectra of 56 Peg in terms of a hydrostatic equilibrium solution with a chromosphere and transition region. It is also significant that the model assuming the presence of coronal material predicts the correct density structure of the atmosphere. Furthermore, a modest magnetic field and dissipation of Alfvén wave flux is consistent with the observed radiative losses.

Although the chromosphere and transition region models can account for the observed line fluxes, the variable asymmetry in the Mg II h and k lines remains a problem. No direct evidence has been found to indicate that 56 Peg is losing mass in a wind, but, in the light of the fact that it violates the rotation-activity correlation by three and a half orders of magnitude (Schindler et al., 1982), the accretion of material onto the white dwarf remains the best explanation for the observed X-ray luminosity. This circumstantial evidence for mass loss, combined with the presence of a transition region modelled above suggests that 56 Peg could be thought of as a hybrid supergiant.

Schindler et al. (1982) also propose that the X-ray illumination gives rise to orbital phase dependent changes in the ionization structure of the wind along the line of sight, and hence to the variable Mg II line asymmetries. A full investigation of X-ray illuminated cool winds might provide additional clues to the structure of this remarkable star.

References

CEPHID BINARIES WITH LARGE MASS RATIOS (M_1/M_2)

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University of Toronto
and
Astronomy Programs
Computer Sciences Corporation

ABSTRACT

Because of the temperature difference between Cepheids and their hot main sequence companions, the properties of both stars can be determined, even for mass ratios (M_1/M_2) larger than 3.9. IUE observations of 3 Cepheid systems (Polaris, FF Aql. and S Sge) are used to drive, or set limits on, the temperature and masses of the companions. Light from the companions of FF Aql. and S Sge from 1200 to 2000 A is consistent with an A5 to A7 main sequence companion for both Cepheids, with a mass of 1.8 M_\odot. This mass for the companion of S Sge is smaller than required by the orbital mass function and an evolutionary mass of the Cepheid, suggesting that the companion may itself be a binary. For Polaris, the mass of the companion must be less than 1.8 M_\odot.

Keywords: Cepheids, binaries, star formation

1. INTRODUCTION

The separations and mass ratios observed in multiple systems are basic data about star formation. The emerging picture for B-stars is that stars with periods shorter than 10 years have a fairly flat distribution of secondary masses [Ref. 2]. For longer periods, the distribution is dramatically different, and the frequency rises steeply as the mass of the companion decreases. 0 stars, on the other hand, seem to be seven deficient in binaries with mass ratios larger than M_1/M_2 = 3 [Ref. 3]. There are observational limitations of these studies: Only O systems with a small amplitude larger than 15 km/s were detected because of atmospheric motions. In addition, corrections must be made for incompleteness. Any further information about systems with primaries of comparable mass, particularly with large mass ratios (M_1/M_2), is useful.

The value of studying Cepheid binary systems to improve our knowledge of mass ratios and separations is clear from Table 1. Because Cepheids are simplified stars, orbits of very small semi-amplitude can be derived. This means that gravitationally bound long period systems can be studied, as well as systems with small mass ratios and low inclinations. IUE adds important data to these studies, in that companions in large mass ratio systems can be detected because of the temperature difference between the secondary and the primary.

2. OBSERVATIONS

The spectroscopic binaries discussed here are well known (Refs. 1, 6, and 9). Redshifts of the systems Polaris, FF Aql. and S Sge is in preparation (Evans, Ref. 4; Welch and Evans, Ref. 11; and Slepicka, Welch, and Evans, Ref. 10 respectively). For all three stars, IUE long and short wavelength spectra have been obtained with medium resolution, examining them in temperature to look for flux from the companion at the shortest wavelengths. At the phases of observation, the temperature and (B-V), of all three stars happen to be very similar, and are best matched by 15 Dra (F7th).

As an example, Figure 1 shows the comparison between the long and short wavelength spectra of FF Aql and 15 Dra. The 15 Dra spectrum in the long wavelength region (Figure 1 b) has been scaled to match the FF Aql spectrum. The same scaling has been applied to the short wavelength spectrum of 15 Dra (Figure 1 a). The excess light from the FF Aql companion is apparent from 1900 to 2000 A. A spectrum of S Sge also shows light from the companion in this wavelength region.

When 15 Dra is subtracted from the spectra of both FF Aql and S Sge, the resulting spectrum of the companion is a good match to an A5V or A7V standard star from the IUE Spectral Atlas. Figure 2 shows the comparison between the subtracted spectrum, S Sge - 15 Dra, and the spectrum of an A5V star (84 FMa). The match is good: both A5V and A7V standard stars match the subtracted spectra of both the companions poorly. Using the mass compilation of Popper [Ref. 7], this corresponds to masses of 1.8 ± 0.2 M_\odot. This information has been added to Table 1.

For Polaris, no light from the companion was found in a comparison with the spectra of nonvariable standard stars. Using 1.8 M_\odot as an upper limit for the companion to Polaris is a generous upper limit, since FF Aql and S Sge demonstrate that such a companion would be found.

Figure 1a. The spectra of FF Aql (solid) and 45 Dra (dots), F7II. All fluxes are in units of ergs cm$^{-2}$ sec$^{-1}$ A$^{-1}$; wavelengths are in Å. The same scaling has been used as in Figure 1b.

Figure 1b. The spectra of FF Aql (solid) and 45 Dra (dots). The 45 Dra spectrum has been scaled to match the FF Aql flux near 2600 Å.

Figure 2. The spectrum of the 8 Sge companion (solid) compared with the spectrum of an AV5 standard star. A spectrum of 45 Dra was scaled to match the 8 Sge composite spectrum near 2600 Å, as is shown in Figure 1 for FF Aql. With this scaling, the short wavelength spectrum of 45 Dra was subtracted from the 8 Sge spectrum to produce the spectrum of the companion in this Figure.
CEPHEID BINARIES WITH LARGE MASS RATIOS (M₁/M₂)

3. DISCUSSION

A simple picture of the evolution of the system has been assumed (no mass loss, or semi-convection), and the visible companions are assumed to be main sequence stars. The data for the companions is summarized in Table 1. Cepheid evolutionary masses are listed (computed as in Evans and Welch, this conference) from luminosities derived from Caldwell’s (Ref. 3) period-luminosity relation. A shorter distance scale (Schmidt, Ref. 8) decreases the mass ratios by less than 10%. Pulsation masses are 0.8 (Caldwell) to 0.6 (Schmidt) of the evolutionary masses.

For S Sge, the mass function (Ref. 6) implies that the mass of a single companion (sin i =90°) must be at least 2.7 M₂ in order to be compatible with an evolutionary mass in Table 1. The companion mass in Table 1 is significantly smaller. The simplest way to remove the disagreement is a companion which is itself a binary. Among the computed Cepheid masses, only a pulsation mass with a short distance scale is compatible with a companion less than 2 M₂.

For the invisible companion to Polaris, an early F main sequence star is the most probable candidate. It would not be detected, in H & E spectra, but is consistent with the mass function and a Cepheid mass. There are two other possibilities for an invisible companion, an evolved red star and a white dwarf. An evolved red star is too massive to be consistent with the mass function and inclination. Estimates (Ref. 4) show that the hottest white dwarfs in the Hyades and the Pleiades (prototypes for a Cepheid companion) would be detected in H & E spectra, but that cooler cluster white dwarfs would not.

When this work is completed on all Cepheid binaries, the individual mass ratios will be available to the limits of Table 1, which will complement the O and B star results. This will provide direct measurements of the frequency and separations of multiple systems containing massive stars, particularly for widely spaced systems.

Acknowledgements. It is a pleasure to thank the U.E. operations and RDAF staff for assistance in obtaining and reducing these spectra. Financial assistance was provided by a NASA grant NAS 5-28719 and an NSERC grant to Dr. J. R. Percy.

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THE ORBIT OF THE CEPHEID AW PER

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ABSTRACT

An orbit for the classical Cepheid AW Per has been derived. Phase residuals from the light curve are consistent with the light-time effect from the orbit. The companion has been studied using IUE spectra. The flux distribution from 1300 to 2000 Å is unusual, probably an extreme BpSi star, comparable to a BTV or BSV star. The flux of the composite spectrum from 1200 Å through V is well matched by F7Ib and BSV standard stars with \( \Delta M_V = 3^m1 \). The mass function from the orbit indicates that the mass of the Cepheid and its companion make AW Per an excellent candidate for a geometric distance determination with the Hubble Space Telescope.

Keywords: Cepheids, binaries, masses, chemically peculiar stars

1. ORBIT

An orbit for the Cepheid AW Per has been derived (Evans, Welch, and Scarfe, Ref. 4), with a period of 13100 ± 1000 days, a semi-amplitude of 11.1 ± 0.0 km s\(^{-1}\), and a mass function of 1.17 ± 0.30 M\(_\odot\). This orbit is compatible with a light-time effect interpretation of the phase residuals in an O-C diagram. The large physical separation between the Cepheid and its companion makes AW Per an excellent candidate for a geometric distance determination with the Hubble Space Telescope.

2. COMPANION

Because of the temperature difference between the Cepheid and its hot main sequence companion, IUE spectra provide 1000 Å of uncontaminated flux in which to study the companion. Although the spectrum roughly matches the flux distribution of a BSV star from the IUE Spectral Atlas from 1170 to 2000 Å, it differs significantly in detail. Figure 1 shows the comparison between long and short wavelength spectra of AW Per and the BSV standard 18 Tau. Specifically, AW Per has excess flux at 1600 Å. We have investigated a number of possible causes for the spectral peculiarities. No known reddening law can produce the flux distribution. The closest analogy is ApSi stars, which show extra absorption at 1400 Å probably due to Si autoionization, and flux redistribution resulting in excess flux at 1600 Å. We have not found a companion star which is as extreme an example as AW Per, but the ApSi star 56 Ari displays qualitatively similar features as compared with a normal B9V star. In searching unsuccessfully for a more exact match with AW Per B, the companion, the spectra of 23 stars were examined, including ApSi, BpSi, HgMn, Be weak stars (especially those in clusters), and even β Lyr, which has excess flux at 1800 Å.

In order to investigate whether AW Per B is a main sequence star, or a more luminous evolved star with nearly the same mass as the Cepheid, we have compared the luminosity of the companion in the SWP region (1200 to 2000 Å) with that of the hot companion of SU Cyg (H7.5 HgMn). This has been done by selecting observations at phases when the Cepheids are nearly the same temperature, and dereddening them. The spectra were then scaled so that the Cepheids have the correct difference in absolute magnitude \( M_V \) according to the period-luminosity-color relation of Caldwell (Ref. 2), making small corrections for the difference from mean light at the time of observation and the contribution from the companion.

Figure 2 show this comparison between AW Per B and SU Cyg. AW Per B is approximately twice as bright as SU Cyg B. For comparison, Figure 3 shows spectra of B7V (10 Eri) and BSV (18 Tau), scaled so that they have the magnitude difference at V given by the ZAMS calibration of Schmidt-Kaler (Ref. 8). The difference in the ultraviolet luminosity between AW Per B and SU Cyg B is consistent with what would be produced by two stars with main sequence luminosity and a difference of one spectral subclass. Attributing the luminosity difference to a small difference in spectral type is plausible, particularly considering the peculiarities in the spectrum of AW Per B.

The AW Per composite spectrum has been compared with standard star spectra from 1200 Å through V. The flux distribution is well matched by an F7Ib supergiant (45 Dra) and a BSV star with a magnitude difference \( \Delta M_V \) of 3.01.

3. DISCUSSION

The mass function from the orbit is 1.17 ± 0.30 M\(_\odot\). This puts a lower limit on the mass of the companion of 4.7 M\(_\odot\), with a 1σ lower limit on the mass of the companion of 3.3 M\(_\odot\), assuming the Cepheid is the more massive star. Using the mass compilation of Popper (Ref. 1), the mass of BSV and BTV stars are 4.2 and 4.0 M\(_\odot\), respectively. If the companion is a 4.0 M\(_\odot\) single star, this implies that sin i = 90°, and the Cepheid is also a 4.0 M\(_\odot\) star. However, the bolometric magnitude difference between the two stars (from the flux
distribution) of 2.45 to 2.82 is too large to be consistent with two stars of nearly equal mass.

These mass estimates for the Cepheid can be compared with evolutionary and pulsation masses computed from the following sources: B-V temperature calibration: Cox (Ref. 3), eq. 1; evolutionary masses: Y = 0.28, Z = 0.02 for all calculations; Becker, Iben and Tuggle (Ref. 1); pulsation masses: Faulkner (Ref. 5). Masses have been computed for both a long distance scale (Caldwell) and a short distance scale (Schmidt, Ref. 7). Both evolutionary masses (6.8 Mo; (Caldwell) and 6.4 Mo; (Schmidt) are much larger than 4.0 Mo. The same is true of the pulsation mass for the long distance scale (5.4 Mo). Only the pulsation mass for the short distance scale (4.0 Mo) is compatible with the mass implied by a single companion.

On the other hand, if the companion is itself a double star, the inclination may be lower, and the mass of the Cepheid may be larger. This is to be investigated with a high dispersion IUE spectrum by Bohm-Vitense, Evans, and Welch.

Acknowledgements: It is a pleasure to thank the IUE operations and RDAO staff for assistance in obtaining and reducing the data. Radial velocities were obtained by DLW during the tenure of a National Research Council of Canada Research Associateship at the Dominion Astrophysical Observatory. This work was supported by NASA IUE Research contract NAS5-28749 with CSC and an NSERC grants to Drs. J. D. Fernie and C. D. Scarfe.

4. REFERENCES


Figure 1. The comparison between AW Per (solid) and a B8V star (dots). The B8V star (18 Tau) has been scaled. The contribution from the Cepheid can be seen for wavelengths longer than 2600 Å. All wavelengths are in Å; all fluxes are in ergs sec$^{-1}$ cm$^{-2}$ Å$^{-1}$. 

THE ORBIT OF THE CEPHEID AW PER

Figure 2. The comparison between AW Per B (solid) and SU Cyg B (dots). The spectra have been scaled according to the difference in absolute magnitude between the Cepheids. See text for discussion.

Figure 3. The comparison between a B7V star (top) and a B8V star (bottom). The spectra have been scaled according to the ZAMS absolute magnitude.
COMPANIONS TO PECULIAR RED GIANTS: HR 363 AND HR 1105

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Astronomy Programs  Astronomy Department  Dept. of Physics and Astronomy
Computer Sciences Corporation  Indiana University  Howard University

We report recent IUE observations of two Tc-deficient S-type peculiar red giants that are also spectroscopic binaries, HR 363 and HR 1105. A 675 min SWP exposure of HR 363 shows emission lines of O I 1304 and Si II 1812 and a trace of continuum. Compared to the M giants, the far UV flux may be relatively larger, indicating a possible contribution from a white dwarf companion, but no high temperature emission lines are seen to indicate that this is an interacting system where mass-transfer has recently occurred. HR 1105, on the other hand, appears to have a highly variable UV companion. In 1982, no UV flux was discerned for this system, but by 1986 C IV was strong, increasing by a factor of 3 in 1987 with prominent lines of Si III], C III], O III], Si IV and N V. Using orbital parameters, these observations are consistent with high activity occurring when the side of the S-star primary illuminated by the companion faces the Earth, but since the IUE data were taken over 3 orbits, a secular change in the UV component cannot be ruled out.

1. INTRODUCTION

It is becoming increasingly apparent that the peculiar abundance red giants (PRGs) of type MS, S, SC and C are a heterogeneous group of objects with different evolutionary histories. One group of these, the stars of considerable s-process element overabundances but without Tc, appear to be more closely related to Ba II stars than to K-M giants and thus may have been mass-transfer binaries in the past (Ref. 1). Under this scenario, the current primary did not evolve into a PRG, but was polluted by material from a companion that once went through this phase. Since the primary itself is not in a thermally pulsating state, its composition reflects that of the PRG phase of the companion, except that elements such as Tc should have decayed away. This companion should now be a white dwarf (WD) star.

The latest list of PRGs that have been searched for Tc is by Little et al (Ref. 2). If the above scenario is correct, the Tc-deficient stars should be binaries with WD secondaries. Two surveys for WD companions of the MS and S stars have been published (refs. 3-4) and companions to a few stars have been discovered serendipitously (refs. 5-6). These observations were undertaken without regard to Tc abundance or indications of binary nature, but have resulted in the discovery of three stars with hot secondaries: HD 35155, HR 1105 and ω Ori. The first two show no Tc but have strong emission lines in the UV, while the third has Tc but no high temperature lines. HD 35155 also has been noted to be highly variable in the UV, both in the continuum and the lines. Thus HD 35155 and HR 1105 may be interacting mass-transfer binaries while ω Ori is not, and the expected correlation with Tc holds. We report here observations on another Tc-poor S star, HR 363, and demonstrate that HR 1105 is also a UV variable as HD 35155 has been found to be.

2. HR 363

HR 363 (S3+/-2-) was noted in the General Catalogue of Stellar Radial Velocities as being a spectroscopic binary, based probably on its velocity variations, but no orbit or period was established. Ake and Johnson (Ref. 4) determined an upper limit on the luminosity of a degenerate secondary based on a quick SWP survey, but due to the importance of this object on the binary hypothesis, we have reobserved it with a longer exposure. Figure 1 shows the resultant spectrum after removing extraneous hits and reprocessing with a Gaussian extraction routine. A low level continuum and emission lines of S I + O I 1300 and S I + Si II 1915 are prominent as is typical in deep exposures of M giant stars (Ref. 7). The stronger emission lines are as noted from high dispersion observations by Carpenter et al (Ref. 8). While there are corresponding excursions in the HR 383 data at some of these points, in general the spectrum is too noisy for positive confirmation. Since HR 363 has a composition dissimilar from the M giants and may have undergone convective mixing, the existence of a chromosphere similar to the M giants should not be automatically assumed.

Since we are looking for a hot companion to HR 363, we are...
interested in whether there is additional continuum flux compared to other stars. While there has been much work done on the emission line spectra of cool giants, little has been said about the general underlying continuum, perhaps because of concerns about scattered light in the SWP. From rough estimates of the contamination, Stickland and Sanner (Ref. 7) argue that the continuum in this region for M giants is not due to grating scatter, but arises from the lower chromospheres in these stars. Since their paper, Basri et al (Ref. 9) have derived an improved scattering model for the SWP. We have calculated the scattered light contribution as prescribed in the revision by Basri (Ref. 10) and find that it cannot contribute more than 25% of the flux at 1900 Å, and likely is below 5%. Thus the far UV continuum in single M giants is real and one must exercise some caution in interpreting the data as evidence for companions.

By the flatness of the spectrum for HR 363, a WD with $T_{\text{eff}} > 15000K$ is not present. In Ref. 4 we describe a method for determining the upper limit to the luminosity of a hot secondary by measuring the average flux in the region 1250 to 1950 Å, converting it to a magnitude scale by computing $m_{1600} = -2.5 \log(f_{1600}) - 21.1$, and using the resultant $m_{1600} - V$ color with similar determinations for field white dwarfs and the absolute magnitude of the primary to compute the upper limit. In Table 1 we present the $m_{1600} - V$ colors for HR 363 as well as for 3 late-type M giants. The data is corrected for the tabulated reddening values, which we obtained for the M giants by comparing published $UBVRI$ observations with mean colors for their spectral type, and for HR 363 from Eggen (Ref. 11). Note that the color for HR 363 is about 0.5 mag bluer than the M stars indicating there is added flux in the SWP region. If the entire continuum in HR 363 is due to a companion, we derive $M_V = 11.2$, but the flux for a WD of this magnitude should curve upwards at the shortest wavelengths (see Ref. 4). If we assume that HR 363 has a chromospheric spectrum comparable to the M giants, we find that the added flux yields $M_V = 11.7$ for the companion, which would then have a flatter energy distribution.

Table 1. Average Fluxes at 1600 Å for Red Giants

<table>
<thead>
<tr>
<th>Star</th>
<th>HR 363</th>
<th>γ Cru</th>
<th>ρ Per</th>
<th>g Her</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Type</td>
<td>S3 +/2</td>
<td>M3 III</td>
<td>M4 II-III</td>
<td>M6 III</td>
</tr>
<tr>
<td>$E(B-V)$</td>
<td>0.05</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>SWP Number</td>
<td>32472</td>
<td>5891</td>
<td>32553</td>
<td>1387</td>
</tr>
<tr>
<td>Exp Time (min)</td>
<td>676</td>
<td>90</td>
<td>240</td>
<td>154</td>
</tr>
<tr>
<td>Observer</td>
<td>Ake</td>
<td>Sanner</td>
<td>Ake</td>
<td>Wing</td>
</tr>
<tr>
<td>$(m_{1600} - V)_o$</td>
<td>9.63</td>
<td>10.24</td>
<td>10.05</td>
<td>10.00</td>
</tr>
</tbody>
</table>

HR 1105 (S3.5/2) is a 596 day spectroscopic binary (Ref. 12) whose secondary was first reported by Peery (Ref. 6). He had obtained 2 SWP exposures of 20 min. and 87 min. duration on the same day, the longer one taken after C IV emission was found in the first image. Interestingly a 20 min. exposure was obtained by O'Brien and Johnson in 1982 and no emission was seen. We have obtained 2 other observations and can confirm the variability of this object. In Figure 2 we show plots of the spectra with the stronger emission lines identified, and in Table 2 we present the integrated line fluxes and a continuum flux centered in the relatively line free region at 1460 Å. Orbital phases from Griffin's determination are also indicated.

The recent observations have caught the system in a higher state than previously seen, with a subsequent decline from December 1987 to March 1988 in both the continuum and...
emission lines. In general, the lines and continuum scale together, with little change in the relative line strengths and the continuum slope, although the continuum is slightly bluer in December 1987. The density sensitive Si III/C III] ratio is essentially unchanged, as are ratios of lines of different excitation. These observations argue that the decline was not associated with a change in the energetics of the system, but rather the total luminosity was reduced by a decrease in the apparent size of the emitting region. Compared to the observation in 1986, however, some variations in the lines are seen, although the exposure is somewhat weak. The continuum flux at 1460 Å is nearly the same in the Feb 1986 and March 1988 observations, but in 1986 N V is weaker and the Si III/C III] ratio is < 1. Thus on a longer time scale, the physical conditions of this system appear to be variable.

4. DISCUSSION

While both HR 363 and HR 1105 are Tc-deficient spectroscopic binary PRGs, their characteristics in the far UV are quite different and the evidence for the mass-transfer hypothesis for the origin of their current abundance peculiarities is not clear. Based on comparison with the M giants, a WD companion to HR 363 can only be inferred. Further analysis of the chromospheres of other red giants is required to confirm that appropriate comparison objects were chosen. From the Stickland and Sanner data, we find that the \((m_{B00} - V)\) color for K and earlier type M giants is even redder, so using other standards would opt for a brighter companion. Finally we note that if excess UV flux is from a WD companion, the absence of high temperature emission lines such as C IV indicates that this is not currently an interacting system like HD 35155 and HR 1105.

For HR 1105, clearly a hot companion is present, but as with the symbiotics, the source of the UV radiation is not clear. The variability and brightness of the continuum indicate that the photosphere of a WD companion is not directly observed. Possible locations of the radiation for systems such as these are an accretion disk around the secondary, a stream between the components, or a hot outer atmosphere of the primary heated by the companion. In the last two cases, the observed changes should be correlated with orbital phase. In Figure 3 we show the points at which the observations have been made. There is

<table>
<thead>
<tr>
<th>Date</th>
<th>SWP No.</th>
<th>Phase</th>
<th>N V</th>
<th>O I</th>
<th>Si IV</th>
<th>C IV</th>
<th>Si III</th>
<th>C III]</th>
<th>((f_{\text{1460}}) ergs/cm²/Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982 Aug 31</td>
<td>17816</td>
<td>4.067</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.63(15)</td>
</tr>
<tr>
<td>1986 Feb 7</td>
<td>27678</td>
<td>6.103</td>
<td>1.38</td>
<td>1.71</td>
<td>2.34</td>
<td>9.27</td>
<td>0.18</td>
<td>0.49</td>
<td>1.80(14)</td>
</tr>
<tr>
<td>1987 Dec 17</td>
<td>33059</td>
<td>7.302</td>
<td>7.60</td>
<td>3.02</td>
<td>6.17</td>
<td>&gt; 27</td>
<td>2.03</td>
<td>1.78</td>
<td>3.01(14)</td>
</tr>
<tr>
<td>1988 Mar 6</td>
<td>33059</td>
<td>7.436</td>
<td>3.80</td>
<td>2.69</td>
<td>1.78</td>
<td>11.7</td>
<td>1.12</td>
<td>0.92</td>
<td>1.63(14)</td>
</tr>
</tbody>
</table>

* Overexposed

Figure 2. Temporal variation of the PRG HR 1105 in the SWP region. Successive plots are offset by 5 x 10⁻¹⁴ ergs/cm²/sec/Å each. Prominent emission features are labelled and continuum slopes are indicated.
Figure 3. Motion of the HR 1105 S-type primary about the system center of mass. Phases at which SWP spectra have been taken are marked.

A general relationship in that the highest state occurred when the hemisphere of the primary illuminated by the companion was nearly face on, while the lowest phase (i.e., no emission seen in 1982) occurred when the primary was in front of the plane of the sky. But except for the observations made in the past year, the data was collected at different orbital cycles, so the correspondences are somewhat suspect since secular variations cannot be ruled out. Further observations are required to confirm if the changes are actually periodic.

6. ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of the IUE staff in obtaining these observations and the GSFC RDAF in the specialized extraction routines. The work by T. B. A. is supported by NASA grant NAS 5-28749.

5. REFERENCES

DIRECT UV OBSERVATIONS OF THE CIRCUMSTELLAR ENVELOPE OF \( \alpha \) ORIONIS

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ABSTRACT

\( \alpha \) Orionis is a red supergiant star with significant mass loss (~ \( 10^{-8} M_{\odot} \) yr\(^{-1} \)). It is known from optical and infrared observations to possess an extended, arc-minute sized, shell of cool material. Attempts to observe this shell with the IUE are described, although the deconvolution of the stellar signal from the telescope scattered light will require further calibration effort.

Keywords: Circumstellar shell; Scattered light; Chromospheres; Ultraviolet Spectroscopy.

1. INTRODUCTION

There exists an arc-minute sized shell of luminous material surrounding the red supergiant, \( \alpha \) Ori. It is observed in the light of the low abundance species, neutral potassium (at 7699\( \AA \) - Honigreut, et al. 1980), and in the far-infrared by IRAS (Stencel, Bauer and Pesce 1988). This fact suggested to us that it might be possible to observe scattered Mg II 2800\( \AA \) photons over a comparable dimension, if the chromospheric ionization fraction is maintained in the outflow. Theoretical predictions of the ionization fraction in the outer atmosphere, by Glassgold and Huggins (1986), as well as direct measurement, using microwave techniques, (Drake and Linsky 1986; Drake et al. 1987), appear to support the expectation that there are numerous Mg ions scattered over large distances in the envelope of \( \alpha \) Ori. IUE is well matched to an investigation of the outer envelope, given the 10 by 20 arc second apertures, which sample dimensions of roughly \( 6 \times 10^{18} \) cm (~ \( 10^3 R_\odot \)) at the distance of \( \alpha \) Ori.

A series of observations were made in the LWP camera, low dispersion mode (IUE program CSJRS), with \( \alpha \) Ori being offset various distances from the center of the Long Wavelength Large Aperture (LWLA), along its major axis. The longest exposure time was 480 minutes, with the star 30 arcseconds from the center of the LWLA. Derived signal levels are provided in Table 1, normalized to an IUE Flux Number (FN) per minute scale. The peak FN levels are in the center of the Mg II emission feature and in the nearby continuum, around 2825\( \AA \). The reported temporal variations in the Mg II emission strength (cf. Dupree et al., this volume) were not considered in the present work. Signal was acquired at all offset positions (Figures 1 and 2), and is comprised of unequal components of (1) background/dark counts, (2) telescope-scattered light and (3) scattered light emanating from the extended circumstellar shell of \( \alpha \) Ori. The challenge is to successfully deconvolve these component signals and thereby reveal the intrinsic stellar signal, which can then be used to estimate the density, ionization and velocity field of the outer envelope.

2. SCATTERED LIGHT CORRECTIONS

In order to remove the detector background (dark count), we averaged the signal in part of the image, off the spectrum, near Mg II 2800\( \AA \). We then subtracted this dark level from the data containing the spectrum data. The residual emission line signal [net FN per minute in Mg II] exhibits an approximate \( d^{-2.3} \) falloff, for offsets (\( d \)) greater than 5 arcsec. The on-source exposure and the image with the LWLA centered 13" away (peak flux at 3" from the star), seem to lie along a steeper slope. Although signal in nearby continuum is weak, its falloff may be even slower. If we use the inner 5 arcsec as a zero-order approximation to the telescope scattered light, it would appear that the signal at
Despite the virtually identical exposures, given the slightly arcsec. The peak signal strengths differ by a factor of 1.5, obtained on opposite sides of the LWLA, at +20 and -20.

trailed not be the most suitable object for establishing the level of
different optical path, the detailed mirror surface influence
theoretically, we also note the non-symmetry in the
a Ori. Another problem with 7 UMa is that the on-source
stars like red
dwarf with a color temperature of about 20,000K. Significant
light component from the residual signal, except for the fol-
division could be used to remove the telescope-scattered light
from the residual signal, except for the follow-
(a) Witt et al. reported scattered light levels in the
LWR camera, not the LWP camera we used. The extra mirror feeding the LWR camera might be expected to in-
crease the absolute magnitude of scattered light. DeBoer and Cassatella (1986) reported on measures of scattered
light in the LWP camera, but unfortunately placed η UMa along the minor axis of the LWLA, and derive an approxi-
mate d⁻³² falloff. We have re-examined their data and agree with their conclusion. In principle, this in-
formation could be used to remove the telescope-scattered light component from the residual signal, except for the fol-
lowing complications:

(b) Unfortunately, at the time of this writing, there are
no data which would allow us to assess the significance of
stellar effective temperature as it relates to the intensity of
telecope scattered light. α Ori is a red supergiant with a
color temperature of about 3500K, while η UMa is a B
dwarf with a color temperature of about 20,000K. Signif-
ificant scattered light has been observed shortward of Ly-α
(1215Å) in the SWP camera when observing F type stars,
although no analogous light has been seen shortward of C
II] 2325Å even in deep LWR or LWP camera observations
of red stars. To investigate the magnitude of this effect,
we propose that off-source observations of bright late-type
main sequence stars, with negligible mass loss [e.g. ε Eri]
should be undertaken. Our eleventh year IUE program,
CMKRS, will pursue this.

3. DISCUSSION

Despite the present ambiguity regarding the correction for
scattered light, we can still examine the implications of de-
tection of Mg II light far from the star. Various authors
have derived mass loss rates for α Ori, typically around
10⁻⁶M₀yr⁻¹. With the observed circumstellar shell expan-
sion of approximately 15 km/sec, this implies a matter den-
sity of ∼10⁴cm⁻³ at 10⁴ radii. From this, we could esti-
imate an intrinsic efficiency for scattering of 2800Å photons
by Mg ions, subject to uncertain assumptions about the
degree of ionization in the outer envelope. Calculations of
the brightness distributions of resonant line photons have
been made by Natta and Beckwith (1986) but their results
are restricted to Sobolev regimes which cannot be applied to
the Mg II line transfer problem in cool supergiants, namely,
low optical depths and generally higher ratios of flow speed
to microturbulence than are present in the expanding chro-
mosphere of α Ori. Judge intends to begin calculations
which remove the Natta and Beckwith [N&D] restriction to αr,
much less than 1 (where α is the Voigt parameter), and to include "diffusive" transfer in the line wings (e.g.
Basri 1979) which inhibit the direct escape processes as in
N&B's calculations. This will enhance the intensity of pho-
ton further out in the circumstellar shell relative to the
N&B results. Drake (1985) found a large effective angular
diameter in Mg II 2800Å for α Boo using this approach.

A more complete analysis of these data is being prepared
for publication elsewhere. We are pleased to acknowledge
the support of NASA grant NAG5-816 to the University
of Colorado, as well as the outstanding help of the Res-
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DIRECT UV OBSERVATIONS OF THE CIRCUMSTELLAR ENVELOPE OF ALPHA ORIONIS


Table 1
\(\alpha\) Ori IUE Data Used, programs CSJRS and OD14Y

<table>
<thead>
<tr>
<th>Image</th>
<th>Offset (arcsec)</th>
<th>Exposure (sec)</th>
<th>Peak FN</th>
<th>Bkgd FN (in Mg II)</th>
<th>Log Net FN/min. (nearby cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWP11600</td>
<td>0&quot;</td>
<td>5 sec.</td>
<td>8.224</td>
<td>~ 0</td>
<td>4.99 (0.00)</td>
</tr>
<tr>
<td>LWP10239</td>
<td>+13&quot;</td>
<td>5 min.</td>
<td>5.519</td>
<td>~ 0</td>
<td>3.04 (-1.95)</td>
</tr>
<tr>
<td>LWP10356</td>
<td>+15&quot;</td>
<td>30 min.</td>
<td>6.830</td>
<td>1.850</td>
<td>2.22 (-2.77)</td>
</tr>
<tr>
<td>LWP11599</td>
<td>+20&quot;</td>
<td>225 min.</td>
<td>12.796</td>
<td>2.475</td>
<td>1.66 (-3.33)</td>
</tr>
<tr>
<td>LWP11598</td>
<td>+30&quot;</td>
<td>480 min.</td>
<td>8.032</td>
<td>3.328</td>
<td>0.99 (4.00)</td>
</tr>
</tbody>
</table>

Note: Offset is to center of LWLA, while peak signal occurs in the aperture at the position closest to the star, generally 10" from the nominal offset. The Log Net FN/min in parentheses are relative to the on-source value. Preliminary values.

Table 2
\(\eta\) UMa IUE Data Used, programs PHCAL and OD33Y

<table>
<thead>
<tr>
<th>Image</th>
<th>Offset (arcsec)</th>
<th>Exposure (sec)</th>
<th>Peak FN</th>
<th>Bkgd FN</th>
<th>Log Net FN/min. [near 2800Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWR2127</td>
<td>0&quot;</td>
<td>0.29 sec.</td>
<td>34.100</td>
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<td>7.36 (0.00)</td>
</tr>
<tr>
<td>LWR6576</td>
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<td>61.524</td>
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<td>5.57 (-1.79)</td>
</tr>
<tr>
<td>LWR6575</td>
<td>+15&quot;</td>
<td>25 sec.</td>
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<td>~ 0.</td>
<td>5.14 (-2.22)</td>
</tr>
<tr>
<td>LWR6570</td>
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<td>22 sec.</td>
<td>6.172</td>
<td>~ 0.</td>
<td>4.22 (-3.14)</td>
</tr>
<tr>
<td>LWR6574</td>
<td>+20&quot;</td>
<td>68 sec.</td>
<td>17.146</td>
<td>~ 0.</td>
<td>4.17 (-3.19)</td>
</tr>
<tr>
<td>LWR6577</td>
<td>-20&quot;</td>
<td>67 sec.</td>
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<td>~ 0.</td>
<td>3.99 (-3.37)</td>
</tr>
<tr>
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<td>4.856</td>
<td>71.1</td>
<td>2.96 (-4.49)</td>
</tr>
<tr>
<td>LWP 0040</td>
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<td>7.556</td>
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<td>6.85 (0.00)</td>
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<td>300 sec.</td>
<td>5.048</td>
<td>258.</td>
<td>2.98 (-3.87)</td>
</tr>
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</table>

Note: Offset is to center of LWLA, while peak signal occurs in the aperture at the position closest to the star, generally 10" from the nominal offset. The T next to the exposure time indicates a trailed exposure, where the effective exposure is 3.7 times the pointed exposure. No corrections for camera sensitivity changes have been made. The Log Net FN/minute numbers in parentheses are relative to the on-source value. Preliminary values.

Figure 1: Positions of the LWLA with respect to \(\alpha\) Ori, for the new LWP observations reported here (Table 1).
Figure 2: Montage of contour maps of spectral images of α Ori, near Mg II at varying offset distances. The images are: (a) LWP 11600; (b) LWP 10239; (c) LWP 10356; (d) LWP 11599; (e) LWP 11598, and (f) LWP 9700 (η UMa, on-source, trailed exposure illuminating entire LWLA, for scale). See Tables 1 and 2 for characteristics of each. Each frame plots a spatial dimension (abscissa, 30 arcseconds full range) versus a spectral dimension (2750 to 2850A). Note the gradient in the signal toward the edge of the LWLA, in the direction of the star (off to the right). Local maximum and minima at marked, units are FN.
MULTI-WAVELENGTH OBSERVATIONS OF THE PECULIAR RED GIANT HR 3126

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ABSTRACT

New ultraviolet observations of the red giant HR 3126 are reported and combined with multi-wavelength data in order to provide a firmer basis for explaining the unique, arc-minute sized nebula surrounding the object.

Keywords: ultraviolet spectrum; peculiar red giant; stellar evolution; symbiotic stars; hybrid stars.

1. INTRODUCTION

The M2 II star HR 3126 (HD 65750, V341 Car, SAO 235638, CPD-57° 1028) is remarkable because it sits near the center of a butterfly-shaped nebula of several arc minutes extent (Dachs et al. 1978) (Figure 1). While other red objects are known to have nebulae (e.g. OH0739-14, Cohen et al. 1985), most are much smaller and often explained in terms of binary star ejection mechanisms. If HR 3126 is a member of the nearby open cluster NGC 2516, the distance (375 pc), main sequence turnoff age (~ 10^8 years) and implied mass (~ 5M_☉) suggest that HR 3126 is a red bright giant past the initiation of helium burning in its core and on the Asymptotic Giant Branch (AGB). Observations of circumstellar lines in the optical spectrum of HR 3126 indicate a mass ejection rate of 2-4 x 10^-7 M_☉ yr^-1 and a wind velocity of 13 km s^-1 (Reimers 1977).

The reflection nebula, IC 2220, associated with HR 3126, has a mass estimated to be 0.7M_☉ from the mean reddening of the starlight produced in the nebula. Perkins et al. (1981) proposed the existence of a circumstellar disk, implying that previous mass estimates (of the nebula) based on extinction are too large. Their estimate of the nebular mass based on the surface brightness, assuming graphite as the dust material, is ~ 0.01 M_☉, which could be produced in the current mass loss phase of HR 3126.

A light curve between 1963-1977 has been constructed for HR 3126 by Dachs et al (1978), who concluded that the star is an irregular variable (V ranges from 6.2 to 7.1), possibly due to variations in the circumstellar extinction, which may occasionally amount to 0.10 per day. This behavior is similar to the M0 Iab supergiant CPD-57° 3507 in NGC 3293 or to the M2e Ia supergiant, µ Cep. The light curve of HR 3126 has remained quasi-constant during the 1980’s, near V = 6.5 (Dachs 1986, private communication).

Figure 1: Photograph of HR 3126 and surrounding nebula, IC 2220, in the V (yellow) spectral region. From a CTIO Schmidt plate of Dachs.
The essentially constant brightness of IC 2220 does not follow the brightness variations of its central star, neither immediately nor with some fixed delay. The B-V and U-B colors of the nebula are bluer than those of HR 3126, as is expected from a pure reflection nebula. Dachs and colleagues have suggested that the nebula appears to be structured by a magnetic field. A spectrum between 5865 and 6745 Å of the brightest knot of IC 2220, about 40'' south of the star, was obtained by R. Mundt at ESO on 1987 February 25. The spectrum of the nebula resembles that of the star showing Na-D and Hα absorption as well as the TiO band at 6150 Å.

From Dachs (1973) the color differences between nebula and star are,

(B-V) = -0.23 ± 0.03

(U-B) = -0.98 ± 0.11

and their ratio,

y = 4.3 ± 0.8

are much larger than the nebulosity around the Pleiades. This difference may be due to the fact that a larger fraction of radiation at shorter wavelengths may be scattered by reflection nebulae around M-type stars than around B-type stars, or IC 2220 may not be a pure reflection nebula. Perkins et al (1981) state that the degree of polarization is typical of reflection nebulae, indicating that the dust grains reflecting the central starlight are not unusual. Excitation of the gas of the nebula by an unknown, faint, blue companion of HR 3126 may contribute to the ultraviolet radiation of the nebula.

Only a few reflection nebulae connected with red giants are known. Late-type giants are known to lose mass and develop dusty shells which are quite close to the star (arcsec rather than arc-min scales). HR 3126 and IC 2220 offer a unique and interesting environment in which to observe these processes under extreme conditions.

We have obtained IUE and other wavelength data to test the hypothesis that the nebula surrounding HR 3126 is a fossil of a rapid mass loss epoch during hydrogen shell burning, several million years ago.

2. OBSERVATIONS

Ultraviolet observations were obtained 1987 Sept. 28 by Stencel and Pesce [IUE program MLJRS]: SWP 31915 (30 minute exposure) and LWP 11744 (159 minute exposure). We infer from the lack of signal in the SWP exposure that the central object is not an interacting binary, such as a symbiotic star (cf. Nussbaumer and Stencel 1988), because the exposure time was more than adequate to reveal bright emission lines in most of the known members of this class of active binary stars. In the LWP image, only Mg II emission and a photospheric continuum longward of about 2700Å were detected. The Mg II emission appears normal for the spectral type, suggesting a chromosphere is present (see Figure 2).

Doggett obtained visual (3800-5200Å region) spectra of HR 3126 on 1987 September 25th and 26th at CTIO. They appear to be typical red giant spectra with the Ca II H and K features, and TiO bands at 4461, 4954 and 5000 Å. The Ba II feature at 4554 Å is present and is possibly enhanced compared to other M giants (see Figure 3). In addition, a 5640-7040 Å region spectrum was obtained by Walter at Cerro Tololo (1987 April 4). The spectrum is normal except for an overly strong Li I line at 6707 Å. Abnormally high lithium abundances have been seen in weak G band and S-type stars (Hartoch 1978, Boesgaard 1970). According to Pilachowski et al (1984), a normal K giant [HD 112127] and similar stars show high lithium abundance with otherwise normal spectra. High lithium abundances in evolved stars have been taken as evidence that the stars have undergone helium shell flashes and are second ascent giants. However, strong lithium lines were observed by Pilachowski et al in several giants in the old galactic cluster, NGC 7789, indicating an abnormally high lithium abundance on the red giant branch (RGB). These observations remove the constraint that the weak G band stars and the HD112127 stars must be ascending the AGB. In addition, Pilachowski et al conclude that lithium abundance declines with temperature on the upper RGB.

In the infrared region, Ten JHKL observations obtained between 1975 and 1982, at the South African Astronomical Observatory, indicate that HR 3126 is a low amplitude variable with ∆J ~ 0.2 mag. Whitelock observed HR 3120 on 1987 September 15/16 and comparison of (J-H), (H-K) and (K-L) colors with a standard star show longwave excesses. She further reports that, although the colors could be those of a Mira variable, the lack of large amplitude variability and the IR spectrum clearly indicate this is not the case. A low resolution (∆λ/λ ~ 0.01) spectrum from 1.2 - 4.0 μm obtained in December 1981 at South Africa is typical of an M giant, the CO strength indicates a type of M3 and there is no sign of Mira-like H2O absorption.

Finally, IRAS observed this object as well, detecting it in all four bands, 12 to 100 μm and with the Low Resolution Spectrograph (LRS). The infrared colors suggest a far infrared excess remains after a 3250K blackbody is subtracted. Further analysis suggest the source was spatially resolved by the IRAS detectors at all frequencies. In addition, in the LRS spectrum, there is no evidence of the 9.7 μm feature associated with silicate dust or the 10.3 μm feature associated with dust composed of SiC. However, spectra obtained by Humphries and Ney (1974) with the 40-inch reflector at Las Campanas Observatory on a system described by Ney and Stein (1968) show the 9.7 and 18 μm features with silicate grains. Their beam size is 10'', and the spectrum they obtain is probably not contaminated by light from the nebula. Surprisingly, Thomas et al (1970), in observations obtained with the IR photometer attached to the 1.25m telescope at Mt. Stromlo and Siding Springs Observatory, find an infrared excess in the 8- to
MULTI-WAVELENGTH OBSERVATIONS OF THE PECULIAR RED GIANT HR 3126

Figure 2: Ultraviolet spectrum of HR 3126 (LWP 11744). Note the presence of the Mg II emission feature and the lack of other high temperature emission lines, which might indicate a hot companion star/ionized nebula.

Figure 3: Portion of the blue visual spectrum of HR 3126 obtained by Doggett. Note the Ba II feature at 4554.4 Å.

• HR 3126 passed through a red giant phase and is now evolving blueward from the top of the RGB. Comparatively high mass loss and dust production during the previous epoch and the continued expansion of that dust shell is the present day IC 2220 nebula. The problem with this alternative is the lithium, which should have been depleted (according to Pilachowski et al. 1984) as the star neared helium-core ignition (and beyond). The ejection mechanism could be provided by the commencement of core helium fusion, either blowing-off a large amount of material or leading to a mass loss rate approximately two orders of magnitude greater than observed today.

• HR 3126 is at the top of the AGB, perhaps at the beginning of the planetary nebula ejection phase. In this scenario, IC 2220 can easily be explained by the period of thermal pulses that AGB stars experience. Since the star possesses no Mira-like qualities it probably is not in the midst of the AGB, but given the uncertainties in mass and \( M_{\text{ini}} \) \( (\Delta M_{\text{ini}} = -4.4 \text{ (Reimers, 1977)}) \), HR 3126 could easily be at the base of the AGB or at the top. However, we again run into the problem of non-depleted lithium abundances.

3. CONCLUSION

Several possibilities exist as to the location of HR 3126 on the H-R diagram and to the formation mechanisms of IC 2220:

• HR 3126 is a red giant branch star, having ejected part of its envelope upon initiation of the first dredge-up (at the base of the RGB) 32,000 years ago. This scenario is consistent with the enhanced lithium abundance observed. However, the problem that remains is the mechanism for ejection: it is not clear that the first dredge-up could power ejection of such a large nebula.

• HR 3126 is a red giant branch star, having ejected part of its envelope upon initiation of the first dredge-up (at the base of the RGB) 32,000 years ago. This scenario is consistent with the enhanced lithium abundance observed. However, the problem that remains is the mechanism for ejection: it is not clear that the first dredge-up could power ejection of such a large nebula.

The IRAS 60μm addscan profile (Figure 5) shows the expected source extension. The full width at 10% maximum corresponds to a shell dimension of 4.12 arc-minutes, compared to 2.49 arc-minutes for the point source, Ceres (see Stencel et al. 1988 for a thorough discussion of Red Giant/Supergiant infrared source extensions). At 375 pc, this corresponds to a shell of 0.45 pc diameter, or twice the diameter of the optical shell. Assuming the current expansion velocity, the age of the shell is approximately 3.2 \( \times 10^4 \) years.

Figure 4 is a multi-wavelength plot of HR 3126, combining all of the observations. In the Infrared, the points that do not fit on the curve are the LRS data. There appears either to be some calibration error, or a broad emission feature is present in the short wave infrared. Re-observation seems necessary.

In a recent paper by Whitelock and Catchpole (1985), the three super-lithium-rich stars observed are Mira variables, or AGB stars. Contrary to the Pilachowski et al. (1984) analysis, these observations support our hypothesis that HR 3126 is somewhere on the AGB. It should be stressed that the effects of stellar evolution on lithium abundances do not appear to be understood, but they are probably an important clue to the evolutionary stage of a red giant star. Could it be that lithium becomes depleted on the upper RGB but is again enhanced as the star moves up the AGB (due to the second dredge-up and thermal pulses)? Much more work needs to be done to determine lithium’s significance and variations with evolution. The multiwavelength data appears to offer the possibility to test atmospheric response to evolutionary changes.
We are pleased to acknowledge NASA support for some of this work under grants NAG5-816, NGT-78005 and JPL 957532, to the University of Colorado. In addition, the I.U.E. Regional Data Analysis Facility (operated for NASA under contract NAS5-28731) at Colorado provided computer support for which we are grateful. Helpful comments from Dr. Carl Hansen are acknowledged.

4. REFERENCES


RECURRENT SHELL INFALL EVENTS IN A B0.5e STAR: HD 58978 1979-1988

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ABSTRACT

We present a study of infall from the circumstellar envelope onto the bright B0.5e star, HD 58978. The available IUE data indicate that the star has been surrounded by a low and moderately ionized circumstellar shell at least 12 times between 1979 and 1988. During six of these episodes, the signatures of cool circumstellar material were redshifted with respect to the photosphere by 20 to 80 km sec\(^{-1}\). The available data indicate that the transition from infall to minimal shell absorption can occur in <10 days, and are consistent either with infall phases lasting up to 6 months, or with infall episodes shorter than 10 to 15 days. The long term behavior of the shell episodes is compared with variability in the stellar wind.

Keywords: Be Stars; outer atmospheres; circumstellar material; mass infall

1. INTRODUCTION

HD 58978 (FY CMa, HR 2555, B0.5I°v, \(v\ sin \ i = 280\) km sec\(^{-1}\) (Ref. 1)) is a comparatively early-type, bright Be star, which has been the subject of sporadic IUE observations from 1979 and into 1986. More frequent observations began in 1986 and will continue into 1989. Peters (Ref. 2) first noted the presence of multiple, low velocity discrete absorption components in C IV and N V. Subsequent IUE spectra have shown that this star has a strong and dramatically variable stellar wind with complex absorption profiles. The wind profiles in this star are characterized by variable high velocity absorption seen in N V, and C IV. Multiple low velocity (0 to -400 km sec\(^{-1}\)) discrete absorption components are present in all of the IUE spectra, although the absorption depth ranges from essentially saturated features to 20 percent below the continuum level. This star is unusual among the early-type Be stars surveyed by Grady, Bjorkman, and Snow (Ref. 3) in showing variable emission in N V, and possibly also C IV. Unlike most of the B0.5e stars observed with IUE, low ionization material is frequently present in outflow, and is particularly easily detected in Si III \(\lambda 1206\) at velocities up to -600 km sec\(^{-1}\).

2. LOW IONIZATION INFALL

In an effort to better understand the complex wind profiles, and dramatic resonance profile variations, regular monitoring of this star was begun in 1986. Red shifted absorption features in lines of low and moderately ionized species were first noted in an IUE SWP observation made on 1987 May 3, which showed unusually strong absorption in the vicinity of the S III lines at 1202 Å. Further inspection of the spectrum showed that similar absorption features were present in all lines of S III (1)\(\lambda 1200\), Si III (4)\(\lambda 1300\), C II, Al III\(\lambda 1854\), 1862, and several Fe III multiplets, especially multiplet 34. Comparison with the IUE spectrum obtained on 1987 March 6 (SWP 30143) showed that the low ionization features had not been present in March (Figure 2). Sharp absorption features in these ions, particularly the excited state lines, are normally not seen in the UV spectra of stars as hot as HD 58978 (Ref. 3), and indicate the presence of a moderately ionized circumstellar envelope.

The shell features observed in 1987 May 3 have radial velocities corresponding to the absorption maximum ranging from +85 to +110 km sec\(^{-1}\). This range of absorption maxima is a real feature of the stellar spectrum, since interstellar lines observed in both that spectrum, and in the

![Figure 1: N V resonance profiles in HD 58978 for three dates in 1987 to 1988. Note the variations in the emission line strength, the amount of absorption in the low velocity discrete absorption components, and in the amount of high velocity wind absorption.](image-url)
IUE spectrum of the same star obtained on 1987 March 6 agreed to within 4 to 5 km s\(^{-1}\), an accuracy typical of IUE’s pointing (Ref. 4). Inspection of the absorption components revealed that the absorption was not distributed in the form of a single approximately gaussian component, but showed considerable red-asymmetry (Figure 3).

Since the discovery of low ionization infall in the spectrum of this star, we have continued to monitor the low ionization lines in this star, and have extended our analysis to the previously acquired IUE data. As shown in Figure 3, the Fe I\(\text{III}\) (34) line at 1895.456 Å is particularly suitable for monitoring the strength and velocity characteristics of the cool circumstellar envelope, since this line does not have a strong photospheric component, lies in a portion of the IUE spectrum with good signal to noise, and is not blended with other circumstellar or interstellar lines.

The IUE spectrum of the same star obtained on 1987 March 6 agreed to within 4 to 5 km s\(^{-1}\), an accuracy typical of IUE’s pointing (Ref. 4). Inspection of the absorption components revealed that the absorption was not distributed in the form of a single approximately gaussian component, but showed considerable red-asymmetry (Figure 3).

Figure 3: Distribution of infalling material as a function of radial velocity on 1987. The 1987 May 3 spectrum is shown in bold. A comparison spectrum taken in 1987 November (SWP 32317) was obtained at a time when the low ionization infall was minimal. The strong absorption feature centered at +29 km sec\(^{-1}\) is interstellar.

Figure 4a shows the circumstellar Fe I\(\text{III}\) \(\lambda\) 1895.456 absorption equivalent widths as a function of time. Radial velocities of the absorption maximum as a function of time are shown in Figure 4b. The 1987 data show that several successive spectra can show infall signatures. As a result, we define infall episodes to be time intervals where all IUE spectra show infall signatures and separated by IUE spectra without infall signatures, or where the interval between observations is more than approximately 2 months. Shell episodes are defined as intervals where the IUE spectra indicate the presence of cool undisplaced circumstellar material. By these criteria, the available IUE spectra correspond to 12 shell and infall episodes, six of which are infall events. Our data are consistent either with infall episodes shorter than 10 to 15 days, the characteristic separation of the 1987 and 1988 data, or at least as long as 41 days, and possibly as long as six months. The IUE spectra obtained in 1987 November indicate that the signatures of low ionization infall can vanish quickly, in as little as 7 days.

Figure 4a: Fe I\(\text{III}\) (34) \(\lambda\) 1895.456 absorption equivalent widths as a function of time.
3. HIGH IONIZATION INFALL

Four IUE spectra, SWP 6963 (1979 day 296), SWP 28457 (1986 day 139), SWP 30392 (1987 day 57) and SWP 32317 (1987 day 318), show no significant low ionization infall. Instead, these spectra show strong absorption components in N V with centroid velocities of +50, +7 with a strong asymmetric tail extending to +113 km sec\(^{-1}\), +150 and +50 km sec\(^{-1}\) respectively. In the 1987 February spectrum, infalling material is visible out to at least +260 km sec\(^{-1}\) (Figure 5). The three more recent spectra showing the high ionization infall are separated by multiples of approximately 280 days from observation to observation. The available R'E data are too sparse to currently determine whether this interval represents a periodic phenomenon in the stellar envelope, although IUE observations planned for the remainder of the tenth and the eleventh episode may be able to address this question.

4. CORRELATION OF INFALL EVENTS WITH WIND VARIATIONS

Correlating the behavior of the cool circumstellar envelope with the stellar wind is complicated by the complexity of the wind profiles, and by the dramatic variability of all portions of the stellar wind profiles. Of the resonance lines, the N V doublet is the most promising for analysis since the resonance lines are infrequently saturated, and the signal to noise in that part of the spectrum is good. The absorption portion of the C IV profile tends to be saturated at low radial velocities in outflow, precluding reliable measurement. The Si IV profiles are dominated by the strong photospheric absorption profiles, making evaluation of the wind absorption more difficult. All of the available IUE spectra show absorption from low velocity (outflow) discrete absorption components which are particularly pronounced in N V. No weak wind episodes, characterized by the absence of discrete absorption components have been observed in the nearly nine years of IUE observations, in contrast to the behavior of many other early-type Be stars.

The discrete components are the most obviously variable portion of the N V profile. Figure 6 shows the total equivalent width for the low velocity discrete absorption features. This measurement includes the low velocity (outflow) components, any undisplaced circumstellar absorption features, and any red-shifted absorption features. The continuum level for the measurements was determined using the local photospheric continuum outside the resonance profile. Due to the uncertain, and variable number of absorption components the equivalent widths are not easily translated into column densities. Figure 7 shows the Fe I 611 A 1895.456 circumstellar material equivalent width plotted against the summed N V discrete component equivalent widths. Despite the scatter in the N V data, the larger N V equivalent widths tend to be associated with the smaller circumstellar Fe III equivalent widths. This is also supported by the detection of red-shifted N V absorption features only in spectra with no detectable Fe III absorption. These results suggest that the ionization balance in the vicinity of the star is variable, perhaps indicating the presence of transient shocks. At present the data are consistent either with temporal variations, or with variability as a result of orbital motion. A more reliable estimate of the periodicity of the N V red-shifted absorption feature will be required to separate temporal variations, which are not uncommon in Be stellar winds, from any orbital effects.

5. DISCUSSION

Infalling material in main sequence stars with appreciable circumstellar material have been reported in interacting binary stars (Ref. 6), and in the protoplanetary disk/A shell star ft Pic (Ref. 7, 8). Signatures of infalling material were present in IUE high dispersion spectra of ft Pic from 1981 December through 1985, and were also visible in Ca II profiles (Ref. 8). The absorption profiles, and velocity range observed in these lines are similar to those seen in the majority of our spectra. High ionization infall has not been reported in ft Pic, and would be unlikely from the erosion of a comparatively cool dust and gas disk, unless that mate-
6. IMPLICATIONS FOR OTHER Be STARS

Grady, Bjorkman, and Snow (Ref. 3) found several Be stars, not known to be interacting binaries, which had wind (outflow) profiles similar to HD 58978. These stars had emission in at least one resonance profile which was more highly ionized than would be expected in a normal B star of comparable spectral type and luminosity class, and also had strong and extremely low velocity discrete absorption components. These stars also showed wind signatures over a wide ionization range, and in at least one case infalling material is present. The other stars have been insufficiently observed to determine whether infall is present at some times or phases. If all of these objects can be shown to be interacting binary stars, the wind peculiarities may reflect the presence of a hot and luminous secondary in the system, a hot spot caused by the collision of the stellar wind and the mass transfer stream, or the presence of an accretion disk.

The available IUE database on stellar winds in B stars is now sufficiently complete, that single observations of the C IV or N V resonance profiles can identify stars with peculiar winds. Since the integration times to acquire IUE spectra tend to be shorter than those required for x-ray observations, UV spectral surveys of early-type stars may prove to be an efficient way of identifying such interacting binary systems for future study.

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IUUE OBSERVATIONS OF A HOT DAO WHITE DWARF:
IMPLICATIONS FOR DIFFUSION THEORY AND PHOTOSPHERIC STRATIFICATION

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ABSTRACT

We have obtained IUUE observations of the DAO white dwarf PG1210+533, including the first high dispersion spectrum of a hybrid H-He object of this nature. In contrast with hot DAs in the 50,000 K temperature range, PG1210+533 shows no narrow interstellar-like metal lines, in spite of an optically observed He/H abundance of $10^{-4}$. This lack of metals makes accretion from the ISM an unlikely source for the He in the PG1210+533 photosphere. A significant discovery in the high dispersion spectrum has been the existence of a sharp, non-LTE like, core seen in the He II $\lambda 1640$ line. Such features have been previously detected in DO white dwarfs. In addition, a small aperture SWP low dispersion observation has also revealed the Ly $\alpha$ profile of PG1210+533 to be surprisingly weak and narrow. Fits of this profile using pure H models yielded a $T_{\text{eff}} = 56,000$ K. Fits of the Balmer H$\gamma$ profile, however, yielded $T_{\text{eff}} = 42,300$ K and $\log g = 8.5 \pm 0.5$ for the same models. It is unlikely that homogeneously mixed H-He atmospheres can resolve the inconsistency between the Ly $\alpha$ and H$\gamma$ features in this star. Stratified models involving thin H atmospheres may be necessary to explain these results.

Key Words: White Dwarfs, Ultraviolet Spectra

1. INTRODUCTION

One of the more surprising things to arise from IUUE observations of degenerate stars has been the discovery of narrow interstellar-like features due to ions of C, N and Si in high dispersion IUUE spectra of many white dwarfs (Refs. 1-2). Prior to this discovery the atmospheres of the vast majority of white dwarfs were commonly regarded as having photospheric compositions of either pure hydrogen (DAs) and pure helium (DOs and DBs). The accepted explanation for this situation lies in the short time scales for the complete chemical stratification of white dwarf atmospheres. Under the strong gravitational field of a white dwarf the lightest element, normally H but perhaps He if the atmosphere is extremely H poor, will form the visible photosphere. The presence of metallic ions implies either an external source of material or some ongoing processes which can counteract the downward forces on He and metal ions.

Certain heavy ions can, under proper conditions, be supported by radiative forces against gravitational settling. In the absence of external influences such as the accretion of interstellar material the primary factors which ought to govern observed abundance patterns of metallic elements are temperature and gravity. A significant number of DAs, covering a wide range of temperature and gravity, have now been observed with IUUE at high dispersion. What has emerged from these observations seems to conform to the expected pattern. For example, as the intensity of the UV radiation field increases with temperature the most readily supported ions, such as Si II, Si III, and Si IV, are observed. At higher temperatures (~35,000 K) ions of C and N are also observed. There are important exceptions to this picture but they all appear to involve DAs of known (Sirius B) or suspected (HZ 43) high gravity. Initial evidence for such a pattern of metal abundances in DAs has been presented in Ref. 2. An effort summarizing nearly all of the available DA high dispersion observations lends further support to this picture (Ref. 3). In hot DO white dwarfs similar metallic features are seen (Refs 4-6). For these hot He degenerates, however, the features tend to be much broader and the presence of O ions becomes apparent.

From observations of hot DAs in the soft X-ray He abundances on the order of $10^{-4}$ to $10^{-3}$ are inferred (Refs. 7-10). It has been suggested that such He is 1) supported by radiation pressure in a manner similar to the metal ions (Ref. 7) or 2) primarily the product of the accretion of interstellar material (Ref. 9). In either case the presence of metal ions could reasonably be expected to correlate with He abundance. Such expectations make DAsOe attractive candidates for observation with IUUE. Unfortunately there exists only one known DAO bright enough to observe at high dispersion with IUUE. This is PG1210+533, a $V = 14.12$ star having an effective temperature of 50,000 K and helium abundance of $\text{He/H} = 10^{-3}$ (Ref. 11).

2. IUUE OBSERVATIONS

On July 1 1987 we obtained a single SWP high dispersion image of PG1210+533 (SWP 31277) using a combined USI/ESA shift for a total exposure of 13 hr. A continuum level approximately 100 DN above background was achieved for wavelengths shortward of 1750 Å. In addition a doubly exposed large and small aperture low dispersion SWP image (SWP 31278) was obtained. The latter were intended to provide a clean H I Ly $\alpha$ profile of the star. Following standard IUUE extraction, the high dispersion image was examined for the presence of any of the metal features which have been previously detected in DA and DO white dwarfs. Specifically, evidence for the following features were sought: Si II $\lambda\lambda 1206.510, 1260.421, 1264.737, 1265.001$; Si III $\lambda\lambda 1294.543, 1296.726, 1298.891$; Si IV $\lambda\lambda 1548.202, 1550.774$; C II $\lambda\lambda 1334.536, 1335.708$; N V $\lambda\lambda 1238.821, 1422.804$; C IV, 1548.202, 1550.774. No metallic features, clearly identified with the star, were found. Characteristic upper limits on the equivalent widths of these features are on the order of 100 mÅ. Only a single interstellar feature due to Si II $\lambda 1260.421$ was observed. This feature, shown in Fig. 1, has an equivalent width of 145 mÅ and a heliocentric radial velocity of $-16.8$ km s$^{-1}$. 

In spite of the fact that no metallic features associated with PG1210+533 were detected, the broad He II $\lambda$1640 line did reveal a central, narrow core. This feature has a saturated equivalent width of 380 mA and a heliocentric radial velocity of -5.8 km s$^{-1}$. In Fig. 2 we show the region of the He II $\lambda$1640 feature at both low (Fig. 2a) and high (Fig. 2b) dispersion. The existence of the He II line had been previously noted by Ref. 11 in an earlier low dispersion SWP image of PG1210+533. The low dispersion profile shown in Fig. 2a, which is a coaddition of the large and small aperture images, has an over all ~ 3 Å equivalent width. The narrow central core of the He II line in PG1210+533 is similar to features seen in the hot DO white dwarf's PG1034+001 (Ref. 5) and HD 149499 B (Ref. 6). In both instances these narrow cores were identified as non-LTE features, analogous to the non-LTE cores seen in H I Balmer lines of moderate temperature DAs (Ref. 12).

3. IMPLICATIONS

This first high dispersion spectrum of a DAO has interesting implications for several current ideas concerning the composition and structure of white dwarfs. First, the lack of any metal lines poses serious difficulties for models which would invoke the accretion of interstellar matter to account for the presence of He in DAOs. As has been pointed out by Ref. 13 the accretion of sufficient interstellar material to explain the observed He abundance in PG1210+533 would also yield observable quantities (assuming solar proportions) of C III, C IV, and N V. Second, the lack of any metal lines in PG1210+533, a 50,000 K H-rich white dwarf, is anomalous in view of the fact that nearly all DAOs observed to date in this temperature range exhibit metal lines (Ref. 3). The most notable exception has been HZ 43 a hot (T$_{\text{eff}}$ = 57,500 K, Ref. 14) DA showing no metal lines. In the case of HZ 43 high gravity (Ref. 14) can be invoked to explain the lack of any metal lines. A similar explanation may hold for PG1210+533 (see below) but this remains uncertain. Third, the non-LTE like core in the He II $\lambda$1640 feature has considerable significance. If this is a non-LTE feature its formation in a fully stratified atmosphere is puzzling. Normally such features are envisioned as being formed at low optical depths high in the photosphere.

The small aperture low dispersion spectrum of PG1210+533 also poses interesting implications. In Fig. 3 we show the H I $\lambda$4101 profile derived from this spectrum together model atmosphere fit to the data. This Ly $\alpha$ profile is surprisingly narrow. Following the technique of Ref. 15 of fitting the Ly $\alpha$ profile in the T$_{\text{eff}}$-log g plane we obtain a best fit temperature of T$_{\text{eff}}$ = 56,000 K ± 5000 K. This is marginally consistent with Ref. 11 who obtain T$_{\text{eff}}$ = 50,000 K ± 5000 K from optical and IUE data. It is not consistent, however, with fits of the same model atmospheres to the Balmer H$\gamma$ profile for PG1212+533 shown in Fig. 4. The H$\gamma$ profile yields T$_{\text{eff}}$ = 42,600 K ± 4000 K and log g = 8.5 ± 0.5. Results obtained from the joint analysis of Ly $\alpha$ and H I Balmer profiles in hot DAs (Ref. 15 and 16) indicate such a large discrepancy is unusual. Although we have used pure H non-LTE models to fit the Ly $\alpha$ and H I Balmer profiles it is unlikely the addition of homogeneously mixed He at an abundance level of 10$^{-4}$ will explain this discrepancy between the line profiles (Ref. 17). It remains to be seen if these results are explainable in terms of a thinly stratified atmosphere in which a thin H photosphere
Fig. 3 The Lyman α profile of PG1210+533 obtained from the IUE small aperture image. The smooth curve is a model atmosphere fit yielding $T_{\text{eff}} = 56,000 \pm 5000$ K.

Fig. 4 The Balmer Hγ profile of PG1210+533 obtained with the Steward Observatory Blue Pluse Counting Reticon. The smooth curve is a model atmosphere fit yielding $T_{\text{eff}} = 42,600 \pm 4000$ K and $\log g = 8.5 \pm 0.5$, a result inconsistent with the Lyα profile in Fig. 3. The weaker feature to the right of the Hγ line is He I λ4471.

overlies deeper He rich regions. It has recently been demonstrated (Ref. 13) that radiative forces are ineffective in maintaining He in DA photospheres. Because of this, such stratified models are receiving increased attention as means of accounting for the He abundances inferred from soft X-ray observations.

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TEMPERATURE DETERMINATIONS OF HOT DA WHITE DWARFS USING IUE CONTINUUM FLUXES

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ABSTRACT

Effective temperatures of 15 DA white dwarfs hotter than 20,000 K were derived from low-dispersion far ultraviolet spectra which were obtained with the International Ultraviolet Explorer (IUE). The analysis was carried out by comparing the observed far ultraviolet fluxes with model fluxes scaled to the V-band flux. Accurate calibration of the IUE spectra is critical for this analysis. We first corrected observations at all epochs to the 1980 IUE calibration using the time-dependent corrections of Bohlin (Refs. 1,2). Taking advantage of the smooth and well-defined continuum fluxes provided by DA white dwarfs, we then used seven white dwarfs for which accurate, independent temperature determinations have been made from line profile analyses to improve the accuracy of the IUE flux calibration. The correction to the original calibration is as great as 20% in individual 5-A wavelength bins, while the average over the IUE wavelength range is 5%. We present both the final calibration correction and the new accurate temperatures for the hot white dwarfs.

Keywords: White Dwarfs, IUE, Ultraviolet, Spectrophotometry

1. INTRODUCTION

Accurate temperature determinations for hot DA white dwarfs are necessary for several reasons. Temperatures are needed for deriving the luminosity function of DA's; the luminosity function then serves to check calculations of cooling rates for these stars. Trace element abundances in DA's result from temperature-dependent processes. Successful confrontation of observational abundance determinations with theory requires that the effective temperatures be known with sufficient accuracy. Also, the upper temperature limit for DA's needs to be determined with precision, because this limit will help constrain post main sequence evolutionary calculations. Additionally, upcoming extreme ultraviolet (EUV) photometric survey missions (Refs. 3,4) are likely to discover hundreds of very hot DA white dwarfs (Ref. 5). Non-EUV measurements will be required to make the accurate temperature determinations necessary for interpretation of the EUV photometric data for these stars (Ref. 5).

Temperatures of DA white dwarfs have usually been based on optical photometric measurements. However, the optical colors become poor temperature indicators for stars hotter than ~25,000 K. Given that FUV continuum fluxes should serve as a more sensitive temperature indicator, an IUE observing program was initiated that specifically targeted DA white dwarfs hotter than 20,000 K (Ref. 6). It was discovered in the course of analyzing the data from that program that the sensitivity degradation of the IUE cameras gave rise to significant errors in the temperatures inferred from the IUE fluxes, compared with optical photometric temperatures. Similar problems had been noted by IUE observers of other object types (Ref. 7). Consequently, the data analysis presented in Ref. 6 was carried out by making a correction to the IUE fluxes which achieved consistency between the FUV-derived temperatures and the optical photometric temperatures. Because of the time dependence of the sensitivity degradation, this correction consisted of using a few well-observed stars from each ~1-year observing epoch to obtain the necessary sensitivity adjustment for that epoch (Ref. 6). Subsequently, efforts were undertaken by other workers to obtain time-dependent corrections which could be used to correct for the time and wavelength-dependent sensitivity degradation of IUE; these corrections are now available (Refs. 1, 2, 8). The stars from the observing program discussed in Ref. 6, as well as a number of archive spectra, were analyzed on the basis of these time-dependent corrections. This paper presents the results of these analyses.

2. DATA ANALYSIS AND RESULTS

The observations were obtained with the IUE's short wavelength primary (SWP) and long wavelength redundant (LWR) cameras operating in the low-dispersion mode. Stars which were sufficiently bright were observed with both cameras. Fainter stars requiring long exposures were observed only with the SWP.

The IUE spectra were reduced with standard IUE processing techniques. For the analysis, the SWP spectra were truncated at the short wavelength end at 1320 Å to avoid the red wing of Lyman α. The SWP and LWR spectra were cut off at 1940 Å, and the LWR data longward of 3100 Å were omitted because of the unreliability of the fluxes beyond that point. The IUE fluxes were then placed on the original IUE flux scale according to the prescription of Bohlin (Refs. 1, 2). This process only corrects for the variation with time of the IUE sensitivity, and is independent of the absolute flux calibration of the IUE instruments. Bohlin's time-dependent correction data set consists of discrete values which are averaged over 1-year time intervals and 5-Å wavelength intervals. Each data point in the observed spectra was modified with a correction value that is linearly interpolated in time but is based on the values for the nearest wavelength. Bohlin estimates that the corrections given by this procedure are accurate to ~1%. This procedure was applied to all the spectra. However, the spectra for WD0004+330, WD0644+375, and WD2309+105 (SWP7747 and LWR6452) were reduced with the old IUE spectral extraction scheme, which was used until November 1983; hence, Bohlin's procedure will not give optimal results for these spectra.
Normalization of the IUE data was accomplished by rationing the FUV fluxes to the V-band flux, given by

\[ f(5490\AA) = 3.61 \times 10^{-17} f_{\text{V-band}} \]

Determination of the effective temperatures was then accomplished by comparing the observed \( f(\lambda)/f(5490\AA) \) to that predicted by model atmosphere fluxes for a given effective temperature. The model atmosphere code used was that developed by Basri (Ref. 9). This code, based on Auer's complete linearization method, treats the atmosphere as being plane-parallel and in LTE. The continuum fluxes produced by this code have been checked against model fluxes published by Shipman and by Wesemael (Refs. 10, 11), and have been found to agree within 1% from the FUV through the visible, for effective temperatures greater than 25,000 K. The models allow the presence of trace helium; however, the helium abundance within the DA range of \(<10^{-2}\) has an effect on FUV/visible flux ratios only at the <3% level. Therefore, a nominal helium abundance of \(10^{-6}\) was used in the model calculations.

The effect of surface gravity on FUV/visible flux ratios is less than 1% over the range \(10^7\) to \(10^9\); hence a value of \(10^8\) was used. Temperature determinations were made by comparing the data with a range of models and interpolating to find the best fit model temperature. The best fit temperature was taken to be that for which

\[ \sum -2.5 \log \left[ \frac{f(\lambda)/f(5490\AA)}{f(\lambda)/f(5490\AA)} \right]_{\text{observed}} - \left[ \frac{f(\lambda)/f(5490\AA)}{f(\lambda)/f(5490\AA)} \right]_{\text{model}} = 0. \]

Evaluation of the residuals of the fits of the models to the time-corrected data revealed systematic variations as a function of wavelength. These variations were of the order of \(\pm 15\%\). The wavelength dependence of the residuals was consistent from spectrum to spectrum. Furthermore, comparison of the temperatures obtained from the corrected IUE fluxes with temperatures obtained from hydrogen line profiles (Refs. 12, 13) indicated that the IUE fluxes were low by 5% on the average.

Several factors might account for the observed discrepancy. For instance, the model physics may be wrong. The stellar atmosphere composition may not be pure hydrogen, or the stars may be reddened. Also, the line profile temperatures may be in error. None of these can explain the wavelength-dependent irregularities in the fluxes; those must result from IUE calibration errors. The uncertainties in the model physics affect the average flux level at the <2% level (Ref. 10). Reddening cannot account for the apparently low FUV fluxes, because these are nearby (<100 pc) white dwarfs for which the neutral hydrogen columns are much less than \(10^{13}\) cm\(^{-2}\). Unless the extinction is highly anomalous, a typical neutral hydrogen column of \(3 \times 10^{13}\) would give \(E_B - V = 0.005\), resulting in an average extinction over the IUE wavelength range of only 1.6%. The temperatures derived from line profile analyses are subject to small uncertainties due to the statistical errors in the data; Holberg (Ref. 12) quotes formal errors of only \(\pm 3,000 \, K\) at 55,000 K. Systematic errors due to instrumental calibration errors over the small wavelength ranges of hydrogen lines are unlikely to significantly affect temperature determinations. Therefore, aside from the possibility of the existence of errors in the model line profiles, the effective temperatures for DA white dwarfs that are derived from hydrogen line profiles are the most accurate available. Consequently, the observed systematic variations between the IUE fluxes and the model fluxes are most likely attributable to errors in the IUE calibration.

In order to reconcile FUV continuum temperatures with the line profile temperatures, spectra from seven white dwarfs were used to obtain a flux correction to the IUE data. The stars used were WD 0030-532, 0501+527, 0549+158, 1254+223, 1620-391, 2111+498, and 2309+105 (1982 observation only). Model fluxes were generated for each of these stars using the effective temperatures given by Holberg (Ref. 12). Ratios of the observed FUV/visible flux ratios to the values predicted by the models were calculated for all seven spectra. These ratios were then averaged together over the same 5-Å wavelength bins used by Bohlin. The resultant flux correction thus consists of the values by which time-corrected fluxes must be divided. The flux correction is shown in Figure 1.

![Figure 1](image)

**Figure 1.** Flux correction to IUE original epoch calibration, binned in 5-Å intervals. Spectra to which time-dependent correction has already been applied are to be divided by the flux correction values.

After application of both the time-dependent and flux corrections to the spectra, the effective temperatures were recomputed. The complete listing of the results obtained is given in Table 1. The absence of any significant variation with temperature of the FUV continuum temperatures compared to the line profile temperatures indicates that any temperature dependent effects which may affect the modeling of either the line profiles or the continuum fluxes are not significant.

Temperatures are given both for spectra which were time- and flux-corrected (Method 1) and for spectra subjected to individual epoch corrections (Method 2) calculated as per Ref. 6. In the current instance, the individual epoch corrections were based on line profile temperatures, rather than on optical photometric temperatures, as had been done in Ref. 6. The epochs for which the corrections were obtained, and the stars used, were: 1980.0 (WD2309+105), 1981.4 (WD2309+105), 1982.6 (WD0050-332, 0549+158, 1620-391, and 2309+105).

It is seen that the two methods are equivalent, giving effective temperatures which differ only trivially. Note also that, although the time-dependent correction cannot be strictly applicable to spectra reduced prior to November 1980, the effective temperatures that are derived using that scheme are very close to the temperatures obtained from the individual epoch corrections.

The errors shown for the IUE continuum measurements are the combined errors arising from uncertainties in the V magnitude, the spectral-signal-to-noise ratio, the values of stellar parameters other than effective temperature, small reddening effects, and errors in the flux correction. In addition, the flux correction error included the published uncertainties in the effective temperatures used for obtaining the flux correction. (Uncertainties in the model fluxes have no effect; the models are used to obtain the flux corrections and to fit the corrected data. Hence, any systematic model-dependent effects would cancel out.) The magnitude of the flux correction error averaged over the IUE wavelength range (for the correction derived from all seven stars) was only \(\pm 1.3\%\) (1 σ),
Table 1. Temperatures of Stars Derived from Different Measures

<table>
<thead>
<tr>
<th>WD Name</th>
<th>IUE Continua</th>
<th>Line Profiles</th>
<th>Optical Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method 1</td>
<td>Method 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{\text{eff}}$</td>
<td>$\text{Error}$</td>
<td>$T_{\text{eff}}$</td>
</tr>
<tr>
<td>0004+330</td>
<td>42.58$^c$</td>
<td>$\pm0.45$</td>
<td>42.84</td>
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<tr>
<td>0050-432</td>
<td>34.15</td>
<td>$\pm0.67$</td>
<td>34.68</td>
</tr>
<tr>
<td>0346-011</td>
<td>39.10</td>
<td>$\pm0.21$</td>
<td>38.33</td>
</tr>
<tr>
<td>0501+527</td>
<td>66.37</td>
<td>$\pm4.76$</td>
<td>63.82</td>
</tr>
<tr>
<td>0549+158</td>
<td>34.03</td>
<td>$\pm0.22$</td>
<td>34.32</td>
</tr>
<tr>
<td>0644-375</td>
<td>21.76$^c$</td>
<td>$\pm0.29$</td>
<td>21.84</td>
</tr>
<tr>
<td>0651-020</td>
<td>35.50</td>
<td>$\pm0.47$</td>
<td>35.84</td>
</tr>
<tr>
<td>1031-114</td>
<td>25.67</td>
<td>$\pm0.36$</td>
<td>25.81</td>
</tr>
<tr>
<td>1033+464</td>
<td>28.38</td>
<td>$\pm2.18$</td>
<td>--</td>
</tr>
<tr>
<td>1254+223</td>
<td>40.67</td>
<td>$\pm0.24$</td>
<td>40.20</td>
</tr>
<tr>
<td>1403-077</td>
<td>45.98</td>
<td>$\pm4.14$</td>
<td>--</td>
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<td>1615-154</td>
<td>31.76</td>
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<td>31.40</td>
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<td>1620-391</td>
<td>24.83</td>
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<td>24.92</td>
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<tr>
<td>2111+498</td>
<td>37.36</td>
<td>$\pm0.22$</td>
<td>36.76</td>
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<tr>
<td>2309+105</td>
<td>50.30$^c$</td>
<td>$\pm4.25$</td>
<td>52.03</td>
</tr>
</tbody>
</table>

*Methd 1 involved using time and flux corrections to IUE spectra as per section 5.3.6.2.
*Methd 2 involved using individual epoch corrections as per section 5.3.6.1.
*Temperatures arc given in 10$^6$ K.
*Errors are 1σ uncertainties.
*Temperatures obtained using Method 1 on these observations are not strictly accurate. See text.
*IUE temperatures were obtained from 1982/142 observations.
*IUE temperatures were obtained from 1979/355 observations.
References: HWB = Holberg, Wesemael, and Basile (Ref. 12). K = Kahn et al. (Ref. 13).

excepting possible flux errors due to uncertainties in the model physics. Shipman has estimated, however, that the model uncertainties are of the order of 2% or less (Ref. 10). The errors in the temperatures of the individual objects were dominated by observational uncertainties in the V magnitudes.

Also listed in Table 1 are the published line profile temperatures and temperatures calculated from published optical photometry. The optical photometric temperatures are taken from Ref. 5. The temperatures obtained from the different measures are consistent in all cases except that of WD0346-011. For this star, the three different measures give three different temperatures, indicating that the atmosphere of this star might not be homogeneous.

3. CONCLUSIONS

The original epoch calibration of IUE produces fluxes for DA white dwarfs which systematically vary with respect to fluxes predicted by model atmospheres. The variations with wavelength are of the order of ±15%. Based on predicted fluxes using effective temperatures of DA white dwarfs derived from fitting hydrogen line profiles, the IUE flux levels after correction for the time-dependent sensitivity degradation are 5% low (averaged over the range 1320 to 3100 Å). DA white dwarfs may be used to derive a flux correction which can be applied to achieve an absolute overall accuracy for IUE spectra of the order of ±2%. 
4. ACKNOWLEDGMENTS

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5. REFERENCES

The ultraviolet emission of accreting magnetic white dwarfs.

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Abstract

The AM Her (pols) and DQ Her (intermediate polars) systems consist of a strongly magnetized white dwarf accreting from a low-mass companion. Most of the emission arises from the release of gravitational energy in X-rays and further reprocessing in UV and optical radiation through the accretion column. Recent EXOSAT observations and new optical data have led to a better knowledge of these systems. A large body of IUE data is also available but has not been fully emphasized. We present here a preliminary analysis of the ultraviolet continuum and emission line characteristics of these systems.

The UV energy distribution is compared to different emitting contributions: the UV flux most probably results from X-ray heating of the column and of the surface of the white dwarf but cannot be explained by cyclotron radiation. The emission line intensities of the different systems are compared. The resonance line intensity ratios are similar for both classes and are generally in accordance with what is expected from photoionization by soft X-rays. However, two of these systems exhibit anomalous ratios, tentatively interpreted as due to abnormal abundances of carbon and nitrogen.

Keywords: UV radiation, X-ray binaries, magnetic white dwarfs, polars, intermediate polars.

1. Introduction

Accreting magnetic white dwarfs are found among X-ray binaries (Ref.62). They accrete matter from a low mass late type companion filling its Roche lobe. The flow is channeled along the strong magnetic field lines onto one or two polar caps. Depending on the spin period of the white dwarf compared to the orbital period, two classes are distinguished: polars in which the white dwarf rotates synchronously with the orbit and intermediate polars (IPs) in which the spin period (a few tens of minutes) is shorter than the orbital period (of the order of a few hours). Up to now 14 polars are known; most of them have been discovered from their X-ray emission. Their period distribution is characterized by a gap between 2 and 3 hours similarly to cataclysmic variables and by an accumulation around 114 minutes. (Ref.25). Precise values of the magnetic field have been determined either from the optical polarization light curves, or from an eventual detection of cyclotron features or Zeeman components. All these methods lead to a value of B ~20-30 Mgauss. Reviews on these systems are given in Ref. 1, 15, 31 and 35.

The intermediate polars are non-synchronous systems: the white dwarf spin period is in most cases a few tens of minutes while the orbital period is usually larger than 3 hours.

The presence of a magnetic field in IPs is strongly suggested by the pulsed X-ray emission, similarly to that observed in X-ray pulsars. Historically the magnetic field was thought to be lower than that of polars and thus the existence of an accretion disc around the white dwarf was proposed (Ref.61, 31). However, King et al.(Ref.30) and Hameury et al.(Ref.24) propose an evolution model in which IPs are considered as the progenitors of polars systems, thus with similar magnetic moments. Indeed, for A0739+103 a circular I-band polarization of 0.25% was detected. This class (around 13 objects) is not so well defined as compared to polars: it includes dwarf novae (SW UMa, GK Per, EX Hya), old novae (GK Per, and may-be DQ Her though it is not detected in X-rays). A recent review on these objects is given in Ref.4 and 39.

All these sources are strong UV emitters. Most of them were observed with the IUE satellite at low spectral resolution, requiring moderately long exposures times which do not allow the study of variability with orbital phase. Very few results were presented concerning the UV observations of these sources. Detailed analyses were done for only AM Her (Ref.28), E1405-451 (Ref.37, 58.) and E2003+225 (Ref.45). Exosat observations of these X-ray binaries have further reprocessed the energy budget from X-ray to IR, even to radio. Since pioneering work on UV emission, it was clearly established that (i) the magnetic field in polars is lower than previously claimed, therefore a strong contribution of cyclotron emission in UV cannot hold anymore, and (ii) the large value attributed to the magnetic field of IPs prevents the presence of a large disc if any around the white dwarf. This leads to reconsider for both classes the origin of the UV continuum.

Here we present the general UV characteristics of the magnetic cataclysmic variables and compare both classes. This study is only preliminary, an exhaustive analysis will be presented elsewhere.

2. UV Characteristics

2a Data selection

The sample of spectra used for this study is not yet complete: a large part was obtained from the Vilspa Data Bank, some of them were taken during our own observing runs. In Tables 1 and 2, col.4 and 6 respectively indicate the number of analysed spectra and, in parenthesis, the total number existing for each source, while col.3 (resp.5) gives the epoch of a selected representative SW i LW spectrum. "*" choice was made on the basis of the following criteria: short and long wavelength images obtained con-
secutively in the large aperture, exposure times multiple or equal to the orbital period, high signal-to-noise ratio. In some cases, they consist of individual spectra, in others they are obtained by averaging several spectra. The standard procedure used in Vilspa to reduce the images was applied. 11 polars were observed with IUE. When spectra exist for low and high states, both were analysed (i.e. AM Her and E1405-451). Short exposure times of CW1 103+254 have allowed to resolve the bright and faint phases present in the orbital light curve: both phases were considered.

Some IPs exhibit outburst states ( SW UMa, A0526-328, EX Hya, GK Per, V426 Oph): here we have analysed UV data during quiescent and outburst states for the two later. The selected spectrum of DQ Her corresponds to out of eclipse. We have included in this class H0542-407 though it does not exhibit X-ray pulsations and E1013-477 previously classified as a polar (Ref.38) and recently suggested to be an IP (Ref.44). The last column in Tables 1 and 2 gives the references in which previous IUE results are presented.

2.5 Analysis
2.5.1 Continuum

Figures 1 and 2 are UV colour-colour diagrams defined from spectral ranges where no strong apparent line is present (centered at 1272.5Å, 1825Å and 2675Å and of respective width 25Å, 50Å and 150Å). For sources for which a colour excess $E_B-V$ is known (see col.4 Table 2) dereddened colours are also reported. In order to compare the UV continuum to several possible contributions, we have also plotted colours corresponding to blackbodies from 20000 to 300000K (dotted line), to white dwarfs (pure hydrogen model atmosphere with $log g=8$, Ref.63), with the same range of temperatures. Thick dashed lines represent blackbody disc models with outer to inner ratio as shown. Thin dashed line is the colour locus of power laws with index between 0 to -4.
outer to inner radius equal to 5 and 100 and temperatures varying from 10000 to 30000K (thick dashed line) and finally the colour locus of power laws, with index varying between 0 and -4 (thin dashed line). No strong differences are observed for both classes: sources are generally found above all these curves, with a more pronounced clustering around the power law curve (with index -1 to -2) for IPs. This indicates a higher slope at short wavelengths than at longer ones. However, DQ Her is flatter in the SWP region. In both states GK Per decreases at short wavelengths (Ref.7,8).

2.b ii Emission lines

As in most cataclysmic variables, the UV spectrum of magnetic accreting white dwarfs exhibits strong resonance emission lines of NV, Si IV and C IV, in addition to an intense HeII 1640Å line. This latter is peculiarly strong for GK Per during its dwarf nova outburst, as it is during nova explosions. In Figures 3 and 4 the line ratio (NV/Si IV) versus (NV/C IV) is reported respectively for polars and IPs. The most striking feature is the extreme position of the polar H0538+608. The ratio (NV/C IV) is also high (>1) for H0542-007 and C. A. Per during outburst.

In Tables 3 and 4 we reported the UV (continuum + line) luminosity (from 1230 to 3100Å) and the line luminosity (including NV, Si IV, C IV, HeII) measured on dereddened spectra and assuming D - 100pc.

3. Discussion

The magnetic white dwarfs in binaries are bright objects in ultraviolet, with a luminosity ranging from $L_{\text{UV}} \sim (0.2-40) \times 10^{30}$ erg s$^{-1}$ for a typical distance of 100pc (Table 1). The brightest objects are found among intermediate polars which, even if one excludes the outburst states of V426 Oph and GK Per, have luminosity in the range $L_{\text{UV}}(1200-3100\AA) \sim (2-30) \times 10^{31}$ erg s$^{-1}$, compared to polar systems with $L_{\text{UV}} \sim (0.2-2) \times 10^{31}$, again if we exclude the AM Her highest state.

The outstanding characteristic is the very high intensity of the emission lines, that are of the same order for both classes ($L_{\text{line}}(1-10) \times 10^{30}$ erg s$^{-1}$) (Table 1). The corresponding line/continuum luminosity ratio is plotted versus the total UV luminosity in Fig. 5 for both classes, ranging from $L_{\text{line}}/L_{\text{cont}} \sim 0.40$ to a much lower value $\sim 0.10$ for most of IPs. The high excitation and the width of the
We recall that the cyclotron emission of the column itself was first considered as a possible contribution to the UV continuum when magnetic fields of the order of $B \sim 10^9$ G were postulated for AM Her systems (Ref.32). However, direct measurements of magnetic fields now yield values of $B \sim 10^6$ G (Ref.50), so that the maximum cyclotron emission is now shifted to optical frequencies. For instance, from detailed modeling of the cyclotron light curves of E1405-451 we have evaluated the maximum contribution of the cyclotron flux in the range 1230-3100 Å to be 2% for E1405-451.

Another promising site of UV emission is the white dwarf itself whose surface could be partially heated during accretion by diffusion from the high temperature polar cap ($T \sim 200000$K). The overall UV flux was found to be reasonably well described in the low state of AM Her (Ref.28) and E1405-451 (Ref.37) by a $T \sim 20000$K white dwarf atmosphere and $T \sim 25000$K for a pure blackbody respectively. The typical luminosity in the range (1230-3100 Å) is $L_{\text{WD}} \sim 2.8 \times 10^{32} (T/5 \times 10^6 \text{K})^2$ ($T/200000$K)$^2$ with $T$ being a bolometric correction of 0.25 and 0.05 for $T \sim 20000$, 50000 and 100000K respectively, so that a typical white dwarf in the range of temperature 20000-400000K could easily explain the observed luminosity. However Fig.1 and 2 show that the UV colours of the polars systems are far from being explained by a simple blackbody or a typical white dwarf atmosphere. Although Heise and Verbunt (Ref.29) proposed a $T \sim 300000$K atmosphere for AM Her in a high state the overall shape of the UV spectrum does not match at all the model at wavelength lower than 1700 Å. To describe the much flatter overall shape of polars one requires at least a temperature gradient around the polar cap in a similar way as for accretion disc models. Recently in the framework of the model described by Frank et al.(Ref.21) Hameury and King (Ref.23) have proposed an alternative explanation to the UV flux: it would result from reprocessing of hard X-rays emitted by diffuse material falling on a polar cap as large as $10^2$ times the surface of the white dwarf. This would also account for the absence of correlation between soft and UV flux in AM Her.

The difference in accretion rates expected to be 10 times greater for IPs than polars, would explain the different values for UV continuum but it is not clear why the UV line intensities do not increase in a similar way. So, this leads to suggest the existence of a complementary contribution in the UV flux for intermediate polars. The first UV studies of this class (see Ref.41) have led to the interpretation that the UV flux is essentially due to the emission of an accretion disc. However no satisfactory model (blackbody or atmosphere) can reproduce the energy distribution without requiring atypical values for parameters such as the accretion rate or the distance (Ref.41, 60). The interaction of the inner part of the disc with the magnetosphere is not well known (Ref.22) but for systems with spin periods of the order of a few tens of minutes ($w_0 \sim 1$) the distribution of the local temperature is unaffected by the magnetic field. In the context of the standard steady state blackbody model, Fig.6 gives the intrinsic disc luminosity for various accretion rates. It shows that in order to explain a maximum luminosity of the order of $10^{32}$ erg s$^{-1}$ one requires a small inner radius, which is incompatible with the presence of a strong magnetic moment of the order of $10^{7}$ G cm$^{-2}$ (Ref.24). The UV excess in IPs compared to polars must be related to the absence of this component: either this last one is strongly absorbed (the hard X-ray data indicate a large column density ($N_H \sim 10^{21-22}$) or the geometry and physical parameters at the bottom of the column are such that this soft blackbody component is found at much lower temperatures. It was already noted that in order to explain the large amplitude of the optical pulsations one requires an increase in the X-ray luminosity larger than the observed one. (Ref.41)
Further observations with a temporal resolution which allows a study of the UV flux modulation with the spin period of the white dwarf are required.

Figure 6: Luminosity for a given accretion rate $\dot{M}$ (g s\(^{-1}\)) of a standard blackbody disc model (Ref.2) versus its inner radius, assuming an outer radius of $5 \times 10^{10}$ cm, a distance of 100 pc and an inclination angle of 90\(^\circ\).

For both classes, the line intensity ratios are generally in agreement with what is predicted from collisional excitation with ion abundances resulting from photoionization by blackbody spectra with $T \sim 15$-45 eV (Ref.29) (see Fig. 3 and 4) (Note that for such extreme values of the density at the bottom of the column it might be incorrect to extrapolate existing photoionization codes)

However the polar source H0538+608 and H0542-407 (which nature is not yet established) and GK Per in outburst exhibit anomalous ratios. For H0538+608 we have interpreted this in terms of abnormal abundances of carbon (deficient by factor 10) and of nitrogen (over-abundant by factor 3) (Ref.12). This can be related with a previous nova outburst. Another possible explanation is that the companion, at the beginning of its evolution was sufficiently massive (>1$M_\odot$) to burn nearly all its carbon into nitrogen in its core, which is revealed after the lost of the external layers stripped by mass transfer (Hameury et al., in preparation).

References


Stellar Activity
ABSTRACT

Low-resolution Mg II spectra have been obtained with the *IUE* for a number of rapidly rotating, spotted K dwarf stars in the Pleiades cluster. These observations show an order of magnitude spread in the chromospheric emission of presumably coeval members of the cluster. The emission is correlated with the stellar rotation rate, being strongest for stars having periods of <1 day and weakest for more slowly rotating stars. The strength of the emission of the rapid rotators lies well above the emission levels that characterize the most active solar-type stars in the field and is significantly stronger than the Mg II emission observed for low-mass pre-main-sequence stars. These new observations indicate that the decay of stellar chromospheric activity with age does not follow any simple rule, such as the oft-cited square-root law or a recently proposed exponential decay law.

Keywords: Pleiades, Stellar Chromospheres, Cool Stars

1. INTRODUCTION

Studies of the Ca H-K lines of solar-type stars in the field and in open clusters (Refs. 1–3) have shown that chromospheric emission declines with age for 1 M☉ stars older than 100 million years. A similar falloff is observed in the strengths of the UV chromospheric and transition region lines of field stars observed with *IUE* (Ref. 4). The time decay of emission follows a square-root power law according to Ref. 2, an exponential law according to Ref. 4, and the sum of two exponentials according to Ref. 3. In Ref. 4 the exponential falloff is from a plateau level defined by the youngest and most active field stars.

At a nuclear age of 75 million years, the Pleiades cluster bridges the age gap between the youngest field stars and their pre-main-sequence predecessors, the T Tauri stars. X-ray emission in the Pleiades was surveyed with the *Einstein Observatory* (Refs. 5–6), and although a number of luminous X-ray sources were identified, many stars in the cluster fell below the *Einstein* detection threshold.

In this paper I summarize preliminary results from an *IUE* survey of chromospheric emission in the Pleiades, based on Mg II spectra of a sample of G and K dwarf stars, which are known to be members of the cluster. Among these stars are a number of rapid rotators with photometric periods <1 day (Refs. 7–8) and rotational velocities >50 km s⁻¹ (Refs. 9–10). It is thought that these stars may have only recently arrived on the main sequence and may have spun up to their high rotation rates during contraction along their pre-main-sequence evolutionary tracks. It is expected that these high rotational velocities will quickly fall to the values typical of more slowly rotating stars in the cluster (perhaps as a result of magnetic braking by stellar winds) and that subsequently the angular momentum of all the Pleiads will decay more gradually with time in accordance with the square-root or exponential laws cited above. The *IUE* observations reported here were undertaken to measure the intensity of chromospheric activity during this brief phase of very rapid rotation.

2. OBSERVATIONS

Low-resolution spectra were obtained with the LWP camera of *IUE* for 13 late G- and early K-type dwarfs in the Pleiades. The exposure times ranged from 40 to 210 minutes. The initial observations of Hα 303, 345, 625, 686, 1039, 1124, and 1883, supplemented by archival spectra of Hα 923 and 2147, are discussed here. Later spectra of Hα 738, 882, 1032, 1531, 2034, and 3163, which have not yet been analyzed, will be discussed in a future publication. Each spectrum was calibrated and measured with standard computer programs available at the Goddard Regional Data Analysis Facility. Figure 1 shows, as an example, the *IUESIPS*-produced Mg II spectrum of Hα 1183, one of the fastest rotators in the cluster. For a few stars, the Mg II spectrum was extracted from the spatially resolved (line-by-line) image in order to suppress emission from the nebulosity that is illuminated by the bright, early-type stars in the Pleiades. For each spectrum, I measured the integrated flux of the emission in the blended Mg II doublet at 2800 Å, or derived a 3 σ upper limit for that feature. To correct for interstellar extinction, I applied the interstellar reddening estimates of Refs. (10) and (11) and assumed a normal ratio of total to selective extinction.
The dependence of chromospheric emission on stellar rotation of the rapid rotators in the Pleiades is at least twice the level defined by the youngest field stars. Also, the emission in cluster stars, such as Hz II 1883, is plotted as a function of the Rossby number, \( N_R \), and V830 Tau. This distinction would remain even if the line strengths were redrawn at a higher Mg II flux level. In comparison with the much younger pre-main-sequence stars, including the dMe-type BY Draconis stars also plotted for comparison are a number of T Tau and naked T Tau stars, whose rotation periods have been determined from photometric variations (Ref. 14) or from a combination of \( \beta \) sin \( \lambda \) measurements with estimates of the stellar radius.

Among the field stars and among the slowly rotating Hyades dwarfs, at \( N_R > 0.25 \), the strength of the Mg II emission is very tightly correlated with the value of the Rossby parameter. According to Ref. 4, the observations of the field stars can be fitted with a Gaussian curve, which rises to a plateau of enhanced activity at small \( N_R \). Along the plateau, activity is independent of rotation, or at most increases slowly with increasing rotation rate (Ref. 15). The Pleiades stars lie along this plateau, scattered among the dMe stars near \( N_R = 0.1 \), but rise to higher levels of activity at smaller \( N_R \). At the smallest \( N_R \) the chromospheric fluxes of the Pleiades are larger than those of the more highly convective, but more slowly rotating naked T Tauri stars by about a factor of 2. The difference appears significant in terms of the usual observational uncertainties for the IUE. It is certainly possible, however, that within the scatter these high levels of chromospheric activity fall along a smooth extension of the rotation-activity relation of the field stars to very small values of \( N_R \). The issue may be decided once the most recent Pleiades spectra have been analyzed.

For the stars plotted in Figure 3, the rotation-activity relation can also be expressed directly in terms of the rotation rate \( \text{Prot} \). If one excludes the pre-main-sequence stars (because at any given \( \text{Prot} \) their activity is extreme, and because there is some controversy about whether their activity is chromospheric in origin), then the Mg II fluxes can be fitted by the least squares regression,

\[
\log R(hh) = -3.71(\pm0.06) - 0.65(\pm0.07) \log \text{Prot}.
\]

This fit has a linear correlation coefficient of \(-0.8\) and a standard deviation, \( \sigma_{\text{FIT}} = 0.25 \). There is no sign of a change in the slope of this relation at short rotation periods, as P. Walter proposed for coronal X-rays (Ref. 16). Given the existing limitations of stellar dynamo theory and of theories of chromospheric heating, one has little guidance in choosing between this result and the Rossby fit.

5. CONCLUSIONS

At the present stage of the analysis, the IUE observations of low-mass stars in the Pleiades cluster reveal a large spread in chromospheric activity, even among stars of closely the same spectral type, and therefore of mass. This variation from one star to the next can be understood in terms of differences in stellar rotation rates, since...
Figure 2. The normalized Mg II flux (the emission-line flux divided by the apparent stellar bolometric flux) is plotted against age for stars in the Pleiades and Hyades clusters (filled circles), solar-type dwarfs in the field (plus symbols on the right-hand side of the panel), pre-main-sequence T Tauri and low-mass weak emission-line stars (plus symbols on the left-hand side of the panel), and naked T Tauri stars (triangles). The solid line is the exponential decay law from Ref. (4).

Figure 3. The normalized Mg II emission line flux is plotted against the Rossby number $N_R$, the ratio of the rotation period to the convective turnover time. Pleiads and Hyades are denoted by filled circles. The plus symbols represent the dG-dM field stars and the pre-main-sequence stars. The solid line is the Rossby relation for solar-type stars from Ref. (4).
the intensity of chromospheric emission appears to be well correlated with the speed at which a star rotates, although the precise form of that relationship is unclear.

The fastest rotating Pleiades dwarfs may be in a brief phase of ultra-rapid rotation which immediately follows their arrival on the main sequence (Ref. 9). Their chromospheric Mg II fluxes are much larger than those of older, more slowly rotating stars in the field, and are also significantly brighter than the fluxes measured for a number of younger pre-main-sequence stars (see Figure 2). This comparison suggests that the onset of rapid rotation among young stars like the Pleiades dwarfs may be accompanied by a surge in chromospheric activity. In turn, if the magnetic dynamo in late-type stars is self-regulating, as some have already proposed (Ref. 17), then this enhanced level of activity may now generate a much stronger stellar wind and cause a much faster decline in rotation and chromospheric activity with time. Thus, consistent with the appearance of Figure 2, the evolution of surface magnetic activity in main-sequence stars may not follow any simple rule, such as the square-root or exponential decay laws that have been suggested in the past. This conclusion remains intact even if the rapidly rotating Pleiades dwarfs are systematically younger than the slowly rotating cluster stars, as suggested by possibly-systematic differences in their lithium abundance (Ref. 18), unless the age spread for lower main-sequence stars in the Pleiades proves to be comparable with the nuclear age of the cluster.

6. REFERENCES

ON THE FLUX-PERIOD AND FLUX-FLUX CORRELATIONS IN LATE TYPE STARS

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ABSTRACT

The analysis of a wide sample of stars including both main-sequence and evolved stars shows that whilst flux-flux correlations are the same for the whole sample (as in Ref. 4), the flux-period relations show a lower dependence on period for evolved stars. A gravity dependence also enters the flux-period relation for evolved stars. The flux-flux and flux-period relations are combined with coronal parameters to express $P_c$, $T_c$ and $B_c$ in terms of the period. All increase with decreasing period, as expected if dynamo action controls activity. Some specific relations between observable quantities are found which could be tested from further observations. Exploratory calculations of the convective zone fields in mildly evolved stars suggests that a larger convective zone field results which could explain the greater emission from evolved stars for a given period.

1. INTRODUCTION

Since the launch of IUE there have been a number of studies of correlations between the fluxes of lines formed in the chromosphere, transition region and corona (hereafter flux-flux correlations) (Refs. 1-4) and between these fluxes and the stellar rotation period (flux-period correlations) (Refs. 5-13). The aim of such studies is to obtain a better understanding of the mechanisms responsible for the presence of activity across the HR diagram, and an improved knowledge of the relationship between the observed activity and dynamo action in the sub-photospheric convection zone which is thought to be the underlying cause of the activity.

With respect to the flux-flux correlations, the most remarkable result is the tightness of the relations between the emission fluxes from different temperature regimes and their lack of dependence on spectral type and luminosity class (Ref. 4).

However there is a clear dependence of activity on stellar rotation rate. The general trend is that activity increases when rotation period decreases. But main-sequence stars with similar periods show different activity as a function of the spectral type and this led some authors to introduce an interior-dependent parameter (Refs. 14-18), namely $r$, the turnover time of the convective cells. Then tighter correlations occur between chromospheric, transition region and coronal activity in main-sequence stars and the parameter $P_{rot}/r$ (Rossby number) which is related to the efficiency of the dynamo mechanism (Refs. 19-21).

Here we analyze a wide sample of active late-type single and binary stars containing both main-sequence and evolved systems. We find that, in spite of the same behaviour concerning the flux-flux correlations, there are two different trends in the flux-period correlations, one for main-sequence stars and other for evolved systems.

We continue the approach of Jordan et al. (Ref. 22) in expressing the flux and period relations in terms of the coronal plasma parameters, $P_c$, $T_c$ and $g*$, and in relating these to the convective zone field, $B_c$, and surface flux, $B_s$, $A_p/A_b$ (Ref. 21 and 23). The aim is to understand the underlying physical parameters that cause the correlations. In the last Section we propose a tentative explanation, based on dynamo action, for the different behaviour of the activity in main-sequence and in evolved systems.

2. SCALING RELATIONS.

Here we analyze the behaviour of the fluxes in the Mg II, C II and C IV lines, and the X-ray flux with the stellar rotation period and several stellar and coronal plasma parameters.

The stellar and flux data have been collected from several sources (Refs. 7, 10-13, 17, 24-27). The sample is composed of 126 stars: 51 single main-sequence stars, 2 single subgiant stars, 9 single giant stars, 12 binary systems containing main-sequence stars, 22 binary systems containing at least a subgiant component and 30 binary systems containing at least a giant component. We include only stars of type G and K since the convection zone properties of types F and M may be different.

In Figures 1 to 4 we show the logarithm of the surface fluxes versus the logarithm of the stellar rotation period. Open symbols are single stars and solid symbols are components of binary systems; triangles represent main-sequence stars, squares are subgiant stars and circles, giant stars. It is clear from the four plots, that in spite of the scatter, the activity levels for main-sequence stars are above those for more evolved objects. This difference has previously been recognized (Ref. 28).

2.1. Main-sequence stars

The improved sample of single main-sequence stars of type GO - late K leads to the following flux-rotation relations,
These are lower powers than found in the smaller samples discussed in Ref. 22. The flux-flux correlations are similar to others in the literature and are,

\[ F_{\text{Mg II}} \propto \log P, \quad F_{\text{C IV}} \propto \log P \]

consistent with the results in Ref. 4, and

\[ F_X \propto F_{\text{C IV}} \propto F_{\text{Mg II}} \]

The X-ray flux can be expressed in terms of the physical parameters, \( P_c \), coronal electron pressure, \( T_c \), temperature, and \( g_* \), gravity, based on the assumption that the radiative losses and conduction losses are proportional to each other. The methods below continue from the work in Refs. 21-23 and the results from these papers will be used here without derivation. This gives the same scaling (but not exactly the same constant of proportionality) as Hearn's minimum energy loss hypothesis (Refs. 29 and 30). Then

\[ P_c = g_* T_c^2 \]

The X-ray emission is assumed to be formed over an \( N_e^2 \) isothermal scale height in an uniform, spherically symmetric corona. This is justified by a direct plot of \( F_x(0) \) or \( E_m(T_c) \) against \( T_c \), for example as shown in Ref. 31, which supports relation (5), particularly when even approximate gravities are included.

By postulating heating by an Alfvén mode at some fixed value of \( \langle B^2 \rangle /B^2 \), the coronal magnetic field is introduced; hence,

\[ B_c^2 \propto P_c \propto T_c^2 g_* \]

Also the energy flux to the corona scales as

\[ F_m(T_c) \propto P_c^{5/4} g_*^{-1/4} \]

and from the analysis of the five main-sequence stars (Ref. 22), \( P_c = P_0 \), where \( P_0 \) is the transition region pressure.

In terms of the period, \( P \),

\[ B_c \propto P_c^{1/2} \propto g_*^{1/6} P^{-2/3} \]

\[ T_c \propto g_*^{-1/3} P^{-2/3} \]

i.e. \( T_c \), \( B_c \) and \( P_c \) increase with decreasing period, supporting the role of stellar rotation.

Relations (1) can then be expressed in terms of the physical parameters, so that

\[ F_{\text{Mg II}} = P_0^{0.60} / g_*^{0.20} \]

\[ F_{\text{C IV}} = P_0^{0.92} / g_*^{0.31} \]

From the study of the five dwarfs, (Ref. 22) it was found empirically that

\[ F_{\text{Mg II}} = P_0^{0.60} / g_* \]

in good agreement with (10), since the spread in gravity is low within the main-sequence stars. Solar models give a dependence on \( M_0 \) (mass column density) that ranges between \( \propto M_0 \) (Judge, private communication) and \( M_0^{1/3} \) (Ref. 32).

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**Figures 1 to 4.** Flux-period correlations for Mg II, C II, C IV and X-rays. See text for symbols.
2.1.1 Non-thermal velocities. Although the transition region area factors cannot be derived, conservation of magnetic flux and non-thermal energy -on the grounds that little energy is lost in the transition region- leads to an interesting prediction which does not depend on area factors.

If $B_{TR} A_{TR} = B_c A*$ and $F_m(TR) A_{TR} = F_m(c) A*$, then using Eq. 7 the non-thermal velocities should scale as

$$<V_{T^2}> \sim (P/\Omega)^{1/4} = T_c^{1/2}$$

Relation (13) is roughly suggested by the five dwarfs (Ref. 22) and the Sun. Although studies of specific giants of known $T_c$ are not available, the general trend is for higher values of $<V_{T^2}>$ and $T_c$ in giants compared with main-sequence stars.

2.1.2 Convection zone and surface fields. The work of Montesinos et al. (Ref. 21) shows that the convection zone field scales as

$$B_{CZ} \propto p^{-0.69}$$

and the surface flux, $B_s A_s$ follows

$$B_s A_s / A_0 \propto p^{-2.03}$$

i.e.

$$B_{CZ} \propto (B_s A_s / A_0)^{0.34}$$

From Eq. 8 one finds $B_c = (B_s A_s / A_0)^{1/3} g_*^{1/6}$, i.e.

$$B_c = B_{CZ}$$

and

$$B_c = (B_s A_s / A_0)^{1/3} g_*^{1/6}$$

Thus $B_c$ depends on the convective zone field and surface flux. However, it is clear that the relation (18) is not consistent with conservation of the magnetic flux from the photosphere to the corona since then $B_c = B_s A_s / A_0$, i.e. only some fraction of the surface flux extends through to the corona. This ratio, $R$, is

$$R = B_c A_s / B_s A_s = g_*^{1/2} / B_s^{1/2} = g_*^{1/2} p^{2/3}$$

Thus although the total flux available and coronal flux increases when $P$ decreases, a greater fraction of the flux extends to the corona in a slow rotator.

It is also obvious that $B_{Mg II} A_{Mg II}$ cannot equal both $B_s A_s$ and $B_c A_c$. In the Sun the $Mg II$ flux has a lower contrast between supergranulation cell boundaries and interiors, but the area factors then lead to comparable amounts of emission for each component. Some authors (e.g. Ref. 33) interpret two components in terms of magnetic and non-magnetic 'basal' fluxes. It seems likely that not all the photospheric flux continues even to the level of $Mg II$.

2.2 Evolved stars

Whilst there is no gravity dependence for the main-sequence stars, gravity does enter the flux-period relations for subgiants and giants which are as follows:

$$F_{C IV} = p^{-0.52} g_*^{0.65}$$

$$F_{C II} = p^{-0.84} g_*^{1.09}$$

$$F_{X} = p^{-0.83} g_*^{1.70}$$

$$F_{X} = p^{-1.42} g_*^{1.70}$$

all lower powers than for the main-sequence stars.

However, the flux-flux correlations are remarkably similar to those of the main-sequence stars,

$$F_{C IV} = F_{Mg II}^{1.60}$$

$$F_{C IV} = F_{C II}^{1.09}$$

$$F_{X} = F_{C IV}^{1.71}$$

$$F_{X} = F_{Mg II}^{2.73}$$

All the factors that depend on the rotation period $P$ then have correspondingly lower powers and a different dependence on $g_*$, for instance

$$T_c \propto g_*^{0.23} p^{-0.47}$$

$$P_c \propto g_*^{1.47} p^{-0.94}$$

However, the flux-pressure relations are similar to those of the main-sequence stars, and in particular

$$F_{Mg II} = P_0^{0.55} g_*^{0.20}$$

Further modelling of giant stars is required to test this, but using values of $P_0$ derived for stars for which both the X-ray flux and temperature are known the correlation seems to hold (See Figure 5).
The different dependence of $T_C$ on period is borne out by the results from Einasto as shown in Figure 6, which plots $\log (T_{C0}/T_{C0,0})$ against $\log P$. The actual predicted dependences for both main-sequence and giant stars agree with the observed trends, although the scatter is quite large. The difference in $T_C$ for stars of the same period, but different gravity is also similar to that predicted.

The ratio $B_{C2}/B_{C5}A_{S}$ cannot be evaluated since reliable convective dynamo models are not available for giant stars. The difference in the dependence of $B_{C2}$ on period between the main-sequence and giant stars is likely to have its origin in a different dependence of $B_{C2}A_{S}/A_{S}$ on $P$.

3. DYNAMO ACTION AND ACTIVITY.

In order to find a theoretical explanation for the different behaviour between the activity levels depending on the evolution stage, we have applied the dynamo model presented in Ref. 20 to several stellar models with the same initial mass but in different evolutionary status in order to compute the magnetic field at the base of the convection zone and its variation over very long time scales. From the value of the magnetic field one can estimate the available magnetic energy in this zone, and compare it with coronal properties.

The basic equations and the formalism of the model are from Refs. 20 and 21. The required parameters describing the conditions in the convection zone for main-sequence stars are from Maeder (private communication) and those for evolved systems have been taken from Refs. 34 and 35.

We present here results for eight models with initial masses 0.9 and 1.0 $M_\odot$. In order to keep some of the assumptions required within reasonable physical limits, e.g. the estimates of $du/dr$, which are based on solar observations, for the more evolved models we use a stellar radius twice that in the main-sequence models.

We show in Figure 7 a plot of the convection zone magnetic field versus the rotation period for the eight stellar models: four for 0.9 $M_\odot$ and four for 1.0 $M_\odot$ (see the corresponding gravities in the plot). It can be seen that the more evolved is a star, the larger is the magnetic field for a fixed period, i.e. the larger is the magnetic energy density available to be released in the atmosphere. As suggested in Ref. 8 this might be expected from a larger convection zone and greater rise time for convective elements.

4. CONCLUSIONS

Expressing flux-flux and flux-period relations in terms of coronal parameters shows that if coronal heating is from an Alfven mode damped at constant $<b^2>$ and $B^2$ then $P_C$, $T_C$ and $B_C$ increase with decreasing rotation period, as expected from dynamo control of activity. A gravity dependence enters the flux-rotation relations for evolved stars, which have a lower dependence on $P$ but greater fluxes. Three specific relations (i) between $<v^{1/2}_{R_0}>$, $P_{C}$, $g_a$ and $T_C$, (ii) between $F_{C2}$ and $P_{C}g_a$ and (iii) between $T_C$, $g_a$ and $P$ are found which could be tested by further observations.

Convective theory extended to mildly evolved stars suggests that for a given period and stellar mass, the more evolved a star is, the greater is the magnetic field generated at the base of the convection zone.

5. REFERENCES

ULTRAVIOLET EMISSION FROM THE SUN AND STARS:
A COMPARISON OF IUE AND SKYLAB SPECTRA

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We present a comparison of IUE low-resolution SWP spectra of late-type stars and of high-resolution Skylab spectra of spatially-resolved solar regions of various degrees of magnetic activity (quiet areas, plages, flares). We degrade the high-resolution solar spectra to the same resolution of IUE and we analyze the solar and stellar data in exactly the same way. We show that the different levels of chromospheric and transition region emission observed in stars of similar spectral types are paralleled by a similar behaviour displayed by solar regions of different magnetic activity. We show that the spatially-resolved solar data obey the same flux-flux relationships as the stellar data over more than three orders of magnitude, with virtually the same slope and similar scatter. We argue that the similar behaviour of the solar and stellar UV line fluxes, together with the dependence of the stellar fluxes on rotation, are indirect evidence that stellar activity is of magnetic origin and likely results from a dynamo process. Finally, we investigate the contribution of blends under different activity conditions, to line fluxes derived from IUE low-resolution spectra. We show that this contribution varies depending on the activity level, and may be substantial for the lines of O I at 1304 Å and He II at 1640 Å.

Keywords: Late-type stars, solar regions, IUE spectra, SKYLAB spectra

1. INTRODUCTION

Ultraviolet emission lines are important diagnostics of the physical conditions in the outer atmosphere of the Sun and late-type stars. By observing stars, we can compare objects with widely different effective temperature, gravity, rotation and age. On the other hand, studies of a bright and extended source like the Sun allow us to investigate the properties of individual regions of different magnetic activity. By comparing the Sun with stars, we can expect to obtain significant insights into the atmospheric properties and magnetic activity in stellar chromospheres and transition regions.

In the past few years, several attempts have been made to compare solar and stellar ultraviolet data (Refs. 1-3). In general, these studies have compared the IUE stellar data with ultraviolet spectra of the integrated solar disk or with representative solar fluxes, and no detailed comparison has been made with high resolution spatially-resolved spectra of individual solar features. In this paper, we present the first detailed comparison of low-resolution IUE spectra of late-type stars with high-resolution spatially resolved SKYLAB spectra of individual solar regions of different activity levels. We show that the comparison provides valuable information on magnetic activity in solar-like stars as well as allowing a better estimate of the contribution of different lines to IUE blended features under different activity conditions.

The IUE satellite has obtained a large number of low-resolution (= 5 Å) ultraviolet spectra of nearby late-type stars over the range 1150-2050 Å. This spectral interval contains lines that are important diagnostics of stellar chromospheres and transition regions. These include the lines of N I at 1241 Å, O I at 1304 Å, C II at 1335 Å, Si IV at 1394 and 1403 Å, C IV at 1550 Å, He II at 1640 Å, C I at 1857 Å, Si II at 1868 and 1871 Å. Lyman-a will not be considered here because it is mostly of geocoronal origin in IUE spectra.

Using the IUE archives, we have analyzed 78 low-resolution SWP spectra, pertaining to 45 different late-type stars. These spectra were chosen from a sample of 131 IUE images: about 40% of the images in the larger sample had to be excluded since they were judged of insufficient S/N ratio. Most of the stars in our sample are main sequence and subgiant stars of spectral types from F8 to G5, i.e. of spectral types and luminosities close to that of the Sun. A few stars, however, were also included of somewhat earlier and later spectral types (as early as F5 and as late as K5) as well as a few binaries of the RS CVn type.

The spectra were first reduced using standard IUE reduction and calibration procedures. Line fluxes were computed by integrating the line profile above a smoothed "pseudo-continuum". The observed fluxes at Earth were then converted into absolute fluxes at the stellar surface (in erg cm⁻² sec⁻¹).

The most striking aspect of the stellar spectra is the extremely large range of emission fluxes which are present even for stars of the same or similar spectral type. This is likely due to the different level of magnetic surface activity in stars, presumably related to differences in age and/or rotation (Ref. 3-5). Active, rapidly rotating stars show transition region and chromospheric lines strongly enhanced (by a factor 10 to 100) with respect to quiet, slowly rotating stars, and the spectra are qualitatively more similar to those of solar active regions and even flares.

2. STELLAR DATA

The solar spectra were obtained in 1973-74 by the Naval Research Laboratory Silt Spectrograph aboard Skylab. These are spatially resolved photographic spectra of individual solar features over the range 1175-1950 Å (Ref. 6). This spectral range is very similar to that covered by the short-wavelength camera of IUE, while the resolution is a factor = 100 better (0.06 Å). The spectrograph slit had a size of 2 arcsec x 60 arcsec (1450 Km x 43500 Km projected on the disk) and was positioned across the solar surface to measure spectra of individual features of different levels of magnetic activity (coronal holes, quiet undisturbed regions, active regions of various activity levels, and flares).

Using the original flight film we scanned at the microdensitometer several spectra of regions of different activity levels. The microdensitometer tracings were done at two different times and using two different microdensitometer machines and associated software. In one set of scans (indicated by diamonds in Fig. 1), a
Figure 1. Flux-flux diagrams between different chromospheric and transition region UV lines. Crosses indicate stars, diamonds indicate spatially-resolved solar regions scanned with a large microdensitometer slit, triangles are solar regions scanned with a small microdensitometer slit. The small rectangular areas in three of the four diagrams refer to the integrated Sun seen as a star. The stellar fluxes are from IUE low-resolution SWP spectra, the spatially-resolved solar data are from NRL Skylab spectra. The integrated solar data are from the Solar Mesosphere Explorer. Notice that the solar and stellar data follow the same flux-flux relationships over more than three orders of magnitude. The correlation coefficients and the best fit lines are indicated.

large aperture was used. In a second set of microdensitometer tracings (indicated by triangles in Fig. 1) we have used instead a small microdensitometer aperture which samples only a small region at the center of the area imaged by the spectrograph slit. However, the NRL spectrograph was not truly stigmatic and each spectral line was nearly uniform from top to bottom: since each line is produced by the solar region selected by the 2 x 60 arcsec slit, these spectra represent some kind of average of the solar area imaged by the slit. There is therefore no significant difference between the two sets of scans.

The microdensitometer tracings were converted into absolute units (erg cm$^{-2}$ sec$^{-1}$ Å$^{-1}$ sr$^{-1}$) using the appropriate density to energy calibration curves and an absolute calibration based on rocket spectra. Since one single D-to-E curve cannot cover the entire spectral range, the spectra were divided into three pieces, which were calibrated separately, and then joined together. In order to allow direct comparison with IUE spectra, the original spectra were then convoluted through a Gaussian filter to degrade the resolution to that typical of IUE. The degraded spectra were then treated in exactly the same way as the stellar data.
UV EMISSION FROM THE SUN & STARS – IUE & SKYLAB DATA

4. COMPARISON OF SOLAR AND STELLAR SPECTRA

There is a strong qualitative similarity between the stellar and solar spectra, when the latter are degraded to the resolution of IUE (see Ref. 7 for a few examples of these spectra). The same lines are observed in both cases, and also similar is the intensity range (spanning more than three orders of magnitude) covered by both stellar spectra and solar spectra of different regions. In general, the spectra of quiet sun areas or of moderately active regions resemble closely those of quiet, slowly rotating stars. The spectra of active regions are more similar to those of active, rapidly rotating stars, while the spectra of RS CVn binaries resemble those of very active solar regions and even of solar flares.

Figure 2a. High resolution (~ 0.06 Å) NRL Skylab spectrum of the O I triplet at 1304 Å. a) Moderately active solar region; b) Solar flare. Notice in the latter case the strong contamination from nearby spurious lines when the spectrum is degraded to the IUE resolution of ~ 5 Å.

Figure 2b. High resolution (~ 0.06 Å) NRL Skylab spectrum of the C II doublet at 1335 Å. a) Moderately active solar region; b) Very active solar region. Notice the absence of any contamination when the spectrum is degraded to the IUE resolution of ~ 5 Å. A similar behaviour is shown by the C IV line at 1550 Å. On the contrary, the line of He II at 1640 Å is strongly contaminated by nearby lines as shown above for the O I line.
Fig. 1 shows flux-flux diagrams constructed using absolute surface fluxes (erg cm\(^{-2}\) s\(^{-1}\)) for both stars and spatially-resolved solar regions. Integrated solar spectra obtained by the Solar Mesosphere Explorer (from Ref. 1) are also shown for comparison. In all cases there is a strong correlation between line fluxes in different chromospheric and transition region lines. The tight correlation observed between different lines indicates that there is a strong coupling between the emission at different atmospheric levels in stellar chromospheres and transition regions. The well-known dependence of stellar activity on rotation (Ref. 3-5), and the similarity of stellar spectra with spectra of solar regions of different magnetic activity, suggests the existence of a casual relationship between stellar magnetic activity and rotation, as might be provided by generation of magnetic fields by dynamo action.

In principle, one could use the flux-flux relationships shown in Fig. 1 to estimate the fraction of the stellar surface covered by regions of different activity levels. Unfortunately, this can be done only in a very qualitative sense, because of the extremely large range of line fluxes covered by both "quiet" and "active" regions. As shown by the solar data in Fig. 1, there is essentially a continuous range of activity levels going from one solar region to another, and we cannot define a typical "quiet" or "active" area. Some qualitative considerations, however, can be done. We see from Fig. 1 that, most of the quiet sun data obtained with the small microspectrophotometer slit are lower in flux than any stellar spectra in our sample, which indicates that even old, slowly rotating stars must have some fraction (a few percent) of their surface covered by magnetic regions. On the other hand, there are stars which globally behave as solar regions of both moderate and very high levels of activity, which indicates that these stars must be entirely covered by active regions of the same activity level as the solar ones (or they must have a smaller fraction of their surface covered by plage regions substantially brighter than the solar ones). Finally, there are a few very active stars (binaries of the RS CVn type) whose lines interrelations (averaged over the stellar disk) are comparable to and even larger than the solar flare analyzed by us: these stars must be covered by active regions that are substantially brighter than typical solar plages.

The availability of high resolution solar spectra for regions of different levels of magnetic activity allows us to check the possible contribution of blends to the low-resolution IUE spectra for stars of various activity levels. The solar spectra show in fact that the most intense UV lines are often accompanied by less intense, on the other hand, there are stars which globally behave as solar regions of both moderate and very high levels of activity, which indicates that these stars must be entirely covered by active regions of the same activity level as the solar ones (or they must have a smaller fraction of their surface covered by plage regions substantially brighter than the solar ones). Finally, there are a few very active stars (binaries of the RS CVn type) whose lines interrelations (averaged over the stellar disk) are comparable to and even larger than the solar flare analyzed by us: these stars must be covered by active regions that are substantially brighter than typical solar plages.

The lowest solar UV fluxes, determined in very quiet areas, lower (by almost one order of magnitude) than those of any star in our sample, and lower than the fluxes of the integrated Sun. This indicates that some magnetic activity (over an area of a few percent of the stellar surface) must be present at any time on all stars in our sample.

The highest stellar UV fluxes are comparable, even during quiet conditions, to line fluxes observed in solar flares or in the most active plage areas. Similarly, these stars must be entirely covered by active regions similar to the most magnetically active solar regions (or that a smaller fraction of their surface is covered by plage areas that are substantially brighter than the solar ones).

- Stellar fluxes in different chromospheric and transition region lines are well correlated to one another, with a typical scatter. Line fluxes for spatially resolved solar regions of different activity levels obey the same flux-flux correlations, with the typical same slope as the stellar data.

- The contribution of unresolved blends to line fluxes estimated from low-resolution IUE spectra changes with the activity level and may be substantial for certain lines (O I and He II). Other lines (C II and C IV) are virtually free of blends under all activity conditions.

In conclusion, the dependence of stellar activity on rotation, and the similarity of stellar spectra with spectra of solar regions of different magnetic activity, suggests the existence of a causal relationship between stellar magnetic activity and rotation, as might be provided by generation of magnetic fields by dynamo action. However, the physical processes that connect together the dynamo process, the generation and dissipation of surface fields, and the response of the atmospheric structure to different energy deposition remain poorly understood.

5. CONCLUSIONS

We can summarize the main conclusions of this work as follows:

- Ultraviolet spectra of stars of different activity levels resemble quite closely ultraviolet spectra of spatially resolved solar regions characterized by different levels of magnetic activity.

- Both solar and stellar fluxes in any individual UV line span more than three orders of magnitude. Line fluxes of quiet, slowly rotating stars are similar to those of solar regions of low magnetic activity. Line fluxes from active, rapidly rotating stars, on the other hand, are similar to those of solar plages and even flares.

- The lowest solar UV fluxes, determined in very quiet areas, lower (by almost one order of magnitude) than those of any star in our sample, and lower than the fluxes of the integrated Sun. This indicates that some magnetic activity (over an area of a few percent of the stellar surface) must be present at any time on all stars in our sample.

- The highest stellar UV fluxes are comparable, even during quiet conditions, to line fluxes observed in solar flares or in the most active plage areas. Similarly, these stars must be entirely covered by active regions similar to the most magnetically active solar regions (or that a smaller fraction of their surface is covered by plage areas that are substantially brighter than the solar ones).

REFERENCES


ABSTRACT

We have obtained a series of high-resolution spectra of the Mg II k line of HD 19917S. We are applying spectral imaging techniques to derive an image of the chromospheric structure and to study the transient behavior of the chromosphere. We have uniformly reduced and analyzed all spectra in the IUE archives, and we are comparing our results with ground-based observations of the photosphere. Four ultraviolet flares on HD 19917S have been observed; 3 of these occurred at roughly the same rotational phase. There is no clear phase-dependence of the SWP line fluxes, but there is for the Mg II k flux. The emission centroid of the Mg II k line varies in a quasi-sinusoidal fashion, presumably due to the rotation of a non-uniform chromosphere.

Keywords: HD 19917S, Spectral Imaging, FK Comae Stars, Chromospheres, Stellar Flares

1. INTRODUCTION

HD 19917S is a G giant star with a v sin i of 80 km s⁻¹ and a photometric period of P=3.337 days, yet it has no measured radial velocity variation (Ref. 1). Its rapid rotation, therefore, probably is not due to spin-orbit coupling in a close-binary system, but perhaps is a result of binary coalescence. Bopp and Stencel (Ref. 2) classified it as one of three known FK Comae stars. The shape and behavior of its visible light curve suggest that its photosphere is non-uniformly spotted and that the photospheric structure changes on yearly, or even monthly, timescales (Refs. 3, 4, and 5). HD 19917S is one of very few stars for which this photospheric non-uniformity has been mapped using Doppler imaging techniques (Ref. 6).

The two low-resolution spectra obtained in 1981 (Ref. 2) showed some suggestion that the SWP line fluxes were brightest near the phase of maximum photospheric brightness (φ=0.5), suggesting a spatial correlation between the chromospheric and photospheric structure. Spectra obtained in 1982 seemed to confirm this suggestion, but the differences were less pronounced.

Because HD 19917S is a single, rapidly-rotating star with bright chromospheric emission lines, we considered it an ideal candidate for an ultraviolet spectral imaging study. We therefore obtained a series of spectra in September 1986. Unfortunately, only 3 unique phases were observed. The high-resolution spectra of the Mg II k (2795 Å) lines showed gross, apparently phase-dependent asymmetries that seemed to be correlated with the large photospheric spot seen in the optical Doppler image (Ref. 6) and perhaps with a scattering patch inferred from linear polarization measurements made in 1982 and 1983 (Ref. 3).

In order to map the spatial distribution of the chromospheric emission, we obtained a series of seven uniformly phased, high-resolution LWP spectra in September 1987. These spectra are being used, in conjunction with those available in the IUE archives, to construct an "image" of the system as seen in the light of Mg II.

We present results of the first phase of this analysis and discuss the measured constraints on the spatial distribution of the chromosphere. These constraints will be used to derive series of images showing the chromospheric brightness distribution at the observed phases. We will compare these images with contemporaneous optical results—Doppler images, linear polarization measurements, and photometry—and with the rotational modulation of the low-resolution SWP line fluxes.

2. SWP LINE FLUXES

All of the low-resolution SWP spectra available in the IUE archives were processed uniformly with the current processing software. Line fluxes were measured by a gaussian fit to the emission line and a quadratic function to the local background (see Ref. 7 for details). The results for C IV (1550 Å), C II (1335 Å), and O I (1305 Å) are shown in Figure 1. The different symbols represent different epochs. All epochs were phased to the ephemeris given in Ref. 4.

The peak C IV fluxes in 1981 and 1982 presumably indicate stellar flares. The C II flux was less enhanced during these
flares, and the enhancement of the O I flux was smaller still. Contrary to earlier conclusions based solely on the 1981 (Ref. 2), 1982, and 1986 fluxes, there is no clear phase-dependence of the line fluxes. The 1987 fluxes are uniformly lower than those at other epochs.

The visible light curve of HD 199178 undergoes abrupt changes in amplitude (Refs. 4 and 5), and it is possible that the epoch of minimum light changes from year to year (Ref. 3). This system has been monitored regularly with the APT and by various observers. During the 1987 observing run, extensive photometry was obtained. A better understanding of the visible light curve is crucial to our interpretation of the ultraviolet variations.

3. TWO-COMPONENT FITS TO THE Mg II k LINES

As a first step in the spectral imaging procedure (see Ref. 8 for a detailed description of the technique), we fit all of the high-resolution Mg II k (2795 Å) spectra with two Gaussian components: one to represent the global chromospheric emission and one to match the (unresolved) interstellar absorption line. In most cases these fits match the overall line profile well, but in a few cases line wing emission well in excess of the fit profile was seen. The parameters of the fitted stellar profiles are summarized in Figure 2.

Two flares (in 1986 and 1987), both at $\phi \sim 0.65$, are indicated by enhanced line fluxes (there was also a flare at this phase in 1981 - see Figure 1). Aside from the flares, there is a clear phase-dependence of the Mg II k flux at all epochs, approximately in anti-phase with the visible light curve. In contrast to the SWP line fluxes, the mean Mg II k flux in 1987 is about the same as that seen at other epochs.

The quasi-sinusoidal variation of centroid velocity (see Figure 2) with phase cannot be due to orbital velocity about a previously unknown companion, because visible spectroscopic observations (Ref. 1) place a much more stringent limit on any velocity variations ($<2$ km s$^{-1}$). The velocity variation therefore is probably due to the rotation of a non-uniformly bright star. A large, bright region in the chromosphere, centered at $\phi \sim 0.5$, could produce the observed velocity variation. The peak Mg II k flux, however, is at $\phi \sim 0.9$, so this region does not account for the variability in the total flux (see Ref. 8 for another example of this phenomenon).
We will re-fit these spectra with a symmetric emission component centered at the predicted radial velocity plus an additional phase-dependent component. This should provide a crude picture of the chromosphere. Any structure is likely large-scale, because no narrow features are seen to move across the line profile as the star rotates.

The measured line widths (Figure 2) are all significantly higher than the stellar $v \sin i$ (80 km s$^{-1}$). The profile was broadened by a tremendous amount during the 1987 flare, and the measured widths in 1987 are all higher than at the previous epochs.

4. REFERENCES


DOPPLER IMAGING OF AR LACERTAE AT THREE EPOCHS

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ABSTRACT

Doppler imaging analysis allows use of the information contained in a time sequence of spectral line profiles to deduce the size, location, and surface flux of regions of contrasting brightness on rotating stars. We have used IUE observations to study the structure of the lower chromosphere of AR Lacertae in the light of Mg II k. We have obtained sequences of LWR/P-H I images distributed around the binary period at three epochs. We have identified discrete plage-like regions of enhanced Mg II surface flux in this system. There are temporal variations in the Mg II flux on timescales of hours as well as substantial changes in chromospheric morphology on timescales of years. Even with the limited S/N attainable with the IUE, one can map the gross structures of active stellar atmospheres. With such information, one can begin to study the true 3-D structure of the atmospheres of late-type stars.

Keywords: Doppler Imaging; Stellar Chromospheres

1. INTRODUCTION

The only star that presents a readily resolvable disk to us is the Sun. Consequently, we have abundant information concerning the surface morphologies of one inactive, unassuming G2 dwarf. Stars, of course, vary widely in their properties. Among the cool, solar-like stars, a number exhibit the "RS CVn phenomenon", i.e., extremely strong solar-like activity, as manifested by strong line emission from the stellar chromosphere and transition region, strong coronal X-ray emission, prominent photometric variability due to the rotational modulation of a spotted hemisphere, and radio emission in some cases. If one takes the observed solar active regions, and increases their filling factors to fill the observed solar disk, one cannot reproduce the levels of activity observed in the most active solar-like stars. In order to understand modelling of these most active atmospheres, it is imperative that one have some grasp on the nature of the surface structures and their filling factors. Does solar analogy apply, as is usually assumed?

The technique of Doppler, or spectral, imaging uses the velocity information contained in the spectral profile of a line, together with knowledge of the stellar rotational velocity and inclination and an assumption about the surface differential rotation, to map features of contrasting brightness at a particular wavelength onto the stellar surface. In principle, the velocity of a feature relative to the rest wavelength of the line (in the frame of the star), in the absence of systematic flows, places the feature on a locus of constant radial velocity on the stellar surface. The acceleration of the feature across the line profile constrains the latitude and altitude of the feature. Further constraints are supplied by the maximum velocity observed and the fraction of the stellar rotational period the feature is visible. This technique was pioneered by Vogel and Penrod (Ref. 1), who used high S/N photospheric absorption line profiles to infer the shapes and locations of the dark photospheric spots on HR 1099.

We have used a conceptually similar technique, described in detail in Ref. 2, involving deconvolution of an emission line into its various components. Our technique is well suited to the lower S/N obtainable for the chromospheric emission lines observable with the IUE. Our target has been AR Lacertae (HD210334: G2IV+K0IV, P=1.056'), at V=6.1 the brightest known, eclipsing RS Camelopardalis system. We have now obtained high dispersion LWR/P spectra of the Mg II k line of AR Lac at three epochs, permitting mapping of discrete structures in the lower chromosphere at these epochs, and giving some indication of the surface morphology of a very active pair of stars.

2. OBSERVATIONS AND ANALYSIS

The number of observations and the phase coverage at each epoch are summarized in Table 1.

The analysis technique is detailed in Refs. 2 and 3. Briefly, we fit the observed Mg II k line profile with up to five gaussian components. Three of the components are well constrained in wavelength, these being the global emission from the two stars in the system and the interstellar ab-
absorption component (which we use as a velocity fiducial to check the IUE wavelength scale). Residuals to the fits containing these 3 components are then fit iteratively until the velocities of the global emission lines agree with those predicted from the orbital elements. The residual features traverse the global line profile as a function of binary phase, indicating that they are due to regions of contrasting surface flux on the stellar surface. Typical line profiles and fits are shown in Figure 1.

3. SUMMARY OF RESULTS
The 1983 results were reported in Ref. 2. Two "plages", regions of high Mg II surface flux, were identified on the surface of the K star. A flare was observed at Mg II and in the radio (2 and 6 cm) and perhaps in N V and C IV. No discrete structures were observed on the G star, and the global fluxes from the G and K stars, exclusive of the plages and flare, did not vary significantly. The plages have filling factors of <.005 and ~.015 of the visible hemisphere of the K star, and Mg II k surface flux enhances by a factor of 5 or more over that of the global emission component. Phase coverage was concentrated near the eclipses and so was not optimal for a Doppler imaging study.

The 1985 results are reported in Refs. 3 and 4. With better phase coverage, we were able to identify 3 discrete plage components on the K star. One plage is at high latitude (50°). The relative sizes, fluxes, and locations of the two equatorial plages are similar to the two observed in 1983; if the same, the plages migrated about 120° towards lower longitudes relative to a purely synchronized star. Filling factors range between 2 and 5% of the visible hemisphere. The equatorial plages appear to lie about half the stellar radius above the photosphere. The G star was observed to flare in Mg II, doubling its emission flux, and the leading hemisphere of the G star was observed to be very dark in Mg II.

The observations in September 1987 were scheduled over two orbital periods in order to reduce ambiguity in interpreting slow changes in the emission fluxes as either slow secular variations or due to rotational modulation. Detailed results are not yet available. However, no flares were observed during these two orbits. The Mg II k line profile of the K star is very similar in appearance to that observed in 1985. The G star appeared to be about 50% brighter on one side, but the dark hemisphere was much brighter than observed in 1985.

![Figure 1: Typical Mg II k line profiles of AR Lac, with multicomponent fits overplotted. These spectra were cover a 19 hour period, and represent half the data obtained in 1985. Note the orbital motions of the G and K stars, plus the persistence of the smaller emission features. From Ref. 3.](image-url)
4. CONCLUSIONS

It is clear that Doppler or spectral imaging observations have the potential of opening up an entirely new perspective on stars. These monochromatic images show the fallacy of modelling such stars using only one component atmospheres. Stellar surfaces are complex, as we should have anticipated from solar images, and it is likely that the solar analogy cannot be stretched far enough to include the most active late type stars without major caveats.

The lower chromosphere, of course, is but one small part of the stellar atmosphere. In order to build up a true 3 dimensional picture of a stellar atmosphere, one must coordinate observations at many frequencies at the same time. How do the structures in the lower chromosphere correspond to the coronal structures inferred from X-ray observations (Refs. 5 and 6)? What spatial relations are there between the plages and the photospheric spots?

We feel it is important to continue these observations, to follow the evolution of the surface structures on AR Lac over a period comparable to the likely stellar cycle period. With the IUE we can obtain excellent phase coverage, which is necessary to discern long-lived spatial features from flares and slower secular variability. We plan to obtain a series of HST/GHRS observations with greatly improved S/N of the Mg II and C IV lines, in order to search for structures in the transition region and to study their relationship to those of the lower chromosphere. Ideally these observations can be undertaken simultaneously with the IUE, providing continuity in phase coverage, and with X-ray and radio observations, in order to yield a true three-dimensional picture of the outer atmosphere of a very active star.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

ROTTATIONAL MODULATION OF HYDROGEN LYMAN ALPHA FLUX FROM 44i BOOTIS

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* Based on observations with the International Ultraviolet Explorer (IUE) obtained at the Villafranca satellite tracking station of the European Space Agency and at NASA/Goddard Space Flight Center.

ABSTRACT

We present IUE observations that cover the entire 6.4 hour orbital cycle of the late-type contact binary 44i Bootis. The intrinsic stellar hydrogen Lyman alpha emission flux was determined from low-resolution IUE spectra, compensating for geocoronal emission and for interstellar absorption. The variation of the stellar Lyman alpha emission flux correlates well with the variation of the CII and CIV emission fluxes, and it shows orbital modulation in phase with the visual light curve. The ratio of Lyman alpha to CII flux (15 to 20) is similar to that observed in solar active regions. Hydrogen Lyman alpha emission is thus one of the most important cooling channels in the outer atmosphere of 44i Boo. We obtained a high-resolution spectrum of the Lyman alpha line between orbital phases 0.0 and 0.6. The integrated flux in the observed high-resolution Lyman alpha profile is consistent with the fluxes determined using low-resolution spectra, and the composite profile indicates that both components of this binary have equally active chromospheres and transition regions. The uncertainty in the interstellar hydrogen column density cannot mimic the observed variation in the integrated Lyman alpha flux, because the stellar line is very much broader than the interstellar absorption.

Key Words: magnetic activity-chromospheres-Lyman alpha emission-ultraviolet spectroscopy-contact binaries

1. INTRODUCTION

The atmospheres of late-type stars consist of relatively cool photospheres, warm chromospheres, and hot coronae. The chromosphere and corona are separated by a thin transition region, in which the temperature changes abruptly from about 7000 K to several million K.

The Lyman alpha line at 1216 Angstroms plays a crucial role in the energetic relationship between the chromospheres and coronae of cool stars. Unfortunately, the possible correlation between the the Lyman alpha line flux and other chromospheric and transition region line fluxes has not yet been investigated, mainly because the very strong Lyman alpha line is generally overexposed on all IUE SWP spectra taken with exposure times long enough to make other interesting spectral features, such as CIV 1550 and CII 1335, visible. In addition, the stellar emission in low-resolution spectra is severely contaminated by scattered solar Lyman alpha emission from the geocoronal environment of the IUE satellite. Further, interstellar absorption can remove a significant fraction of the intrinsic stellar flux from the line.

Nearby contact binaries are good targets to study the Lyman alpha emission, because they are expected to have strong emission and because their emission lines are rotationally broaded so that interstellar absorption does not remove a large fraction of the total flux. In addition, the short periods of contact binaries allow an orbital modulation study to be made. It is possible to perform a simultaneous study of the Lyman alpha line and many chromospheric and transition region emission lines from the contact binary system 44i Bootis with short SWP exposures (which would not be saturated at Lyman alpha). In addition, 44i Boo is bright enough that a high resolution Lyman alpha spectrum can be obtained (although over a large spread in orbital phases), allowing an important check on the techniques used to remove the effects of geocoronal emission and interstellar absorption from the low-resolution spectra.

2. OBSERVATIONS AND CORRECTION FOR THE GEOCORONAL EMISSION AND INTERSTELLAR ABSORPTION

44i Bootis (HD 133640; SAO 45357) is a contact binary at a distance of 12 pc. It has been well studied with the IUE (Rucinski and Vilhu 1983) and with the EINSTEIN (Crudace and Dupree 1984) and EXOSAT (Vilhu and Heise 1986) observatories.

The amplitudes of the radial velocity variations are K1=115 km s-1 and K2=231 km s-1 (Batten, Fletcher, and Mann 1978). The mass ratio is M2/M1=0.50, and the orbital inclination i=77° (Rucinski 1973). The ephemeris of light minimum given in Vilhu and Heise (1986) needs to be corrected by 0.015 days to be consistent with the July 1986 photometry of Al-Naimiy et al. (1986). We used the orbital ephemeris JD(min)=2439852.5035 and an orbital period of 0.2678159 days.

The low-resolution SWP observations were performed on 28 June 1986 during a contiguous US2+ESA double shift (16 hours), covering roughly one orbital cycle. A high-resolution spectrum was obtained on 6 July 1986, with an exposure begun at about primary minimum lasting until secondary minimum (one half of the orbital cycle).

Fig. 1. Model profiles for the Lyman alpha emission line for 44i Boo. The models include the rotational and intrinsic broadening of both components and the absorption due to interstellar hydrogen. Models were computed for three hydrogen column densities ($10^{17}$, $10^{18}$, and $10^{19}$ atoms cm$^{-2}$) and for three orbital phases. The intensity scale is arbitrary, and wavelength (horizontal) scale (km s$^{-1}$) has its origin at the binary's center of mass.

Fig. 2. The fraction of stellar Lyman alpha emission that is absorbed as a function of the hydrogen column density and orbital phase.

Fig. 3. The stellar Lyman alpha, CI 1335, and CIV 1550 emission line light curves of 44i Boo. The visual points from the IUE Fine Error Sensor (FES) and the computed synthetic visual light curve (SYNTH) are marked.
All reduction and analysis of the IUE observations was performed using software at the Colorado Regional Data Analysis Facility (RDAF). After applying the standard flux calibration to the one-dimensional extracted spectra, the Lyman alpha, CII (1335 Angstroms), and CIV (1550 Angstroms) were determined by fitting a gaussian emission profile to the spectral line and a quadratic function to the local background.

Solar Lyman alpha emission is resonantly scattered into the line of sight by hydrogen in the "geocorona". The major axis of the elliptical large aperture is oriented roughly perpendicular to the dispersion in low-resolution spectra and roughly parallel to it in high-resolution spectra. From the geosynchronous orbital position of the IUE spacecraft, geocoronal emission is seen from all directions, therefore uniformly illuminating the aperture. The intensity of the two-dimensional (spatial and spectral dimensions) geocoronal profile varies with the angle between the line of sight and the sun (the Beta angle), the angle between the line of sight and the Earth, and the intrinsic variability of the solar Lyman alpha (Clarke 1982), but the shape of the profile is due solely to instrumental factors. This profile shows light loss near the edge of the aperture due to the point-spread function of the telescope and is roughly flat across the center of the aperture.

We subtracted the geocoronal profile from the low-resolution SWP images using the method developed by Neff et al. (1986). The correction procedure operates on the standard line-by-line (ELBL) files, which include a series of spatially resolved spectra. These spatially resolved spectra are treated as an "image" of the aperture. Geocoronal emission is present throughout the aperture, while the stellar emission is confined to the center of the aperture. We fitted a model profile perpendicular to a dispersion (i.e. in the spatial dimension) at each wavelength within the aperture. This profile was subtracted from each spatial slice to produce a corrected line-by-line file, which may then be co-added with standard IUE software to yield the stellar spectrum with the geocoronal background removed.

The geocoronal model profile consists of gaussian wings fit to the outer portion of the aperture (where light loss is significant) and a linear interpolation across the center of the aperture (the central 11 pixels in the line-by-line spectrum). We therefore use the information within the aperture but outside the region that contains stellar emission to determine the intensity level of the geocoronal emission. Thus, this procedure will work with any spectrum in the IUE archives. This profile has proven to give a satisfactory fit in cases when only the geocorona was observed (sky background or quasar spectra, Neff et al. 1986). For this particular set of observations the stellar emission was strong and exposure times short, so the geocoronal contribution was relatively small.

Because the Lyman alpha line profile is not resolved in low-resolution observations, the only way to estimate how much of the stellar flux is removed by interstellar absorption is to model both the stellar emission and interstellar absorption profiles. The only observational constraint available in the low-resolution spectra is the total integrated flux in the earth-received profile. Other parameters of the model must be constrained with prior knowledge or else varied between their reasonable limits. We used the method described by Rucinski, Vilhu, and Whelan (1985), who argued that since the stellar profiles of contact binaries are very broad (rapid rotators), the interstellar absorption is not extremely large unless the interstellar hydrogen column density is greater than 10^{19} cm^{-2}. For narrow-lined stars the situation is quite different, as even very small column densities cause the interstellar absorption to affect the entire stellar emission profile.

Figure 1 shows a set of theoretical Lyman alpha emission line profiles for 44i Boo computed with the code kindly provided by Dr S.M. Rucinski. This code was described by Rucinski, Vilhu, and Whelan (1985) in their similar study of W UMa. For 44i Boo we used the mass ratio 0.5, the orbital inclination 77 degrees, and the contact fill-out factor 0.9 (as given in Rucinski 1973). We used different interstellar hydrogen column densities, although the most probable value is less than 10^{18} cm^{-2} (Vilhu and Heise 1980).

The system radial velocity of 44i Bootis, with respect to the sun, is 3.4 km s^{-1} (Batten, Fletcher, and Mann 1978). The long astrometric orbit does not affect this value significantly. Using the flow vector for the local interstellar medium (1, b, v) = (258°, 10°, -28 km s^{-1}) from Crutcher (1982), the radial velocity of the interstellar gas in the direction of 44 i Bootis is -12.6 km s^{-1}. In this way we deduce that the interstellar gas is moving with respect to 44i Boo with a velocity of approximately -16 km s^{-1}. This value was used in modelling the interstellar absorption.

Figure 2 shows the fraction of the total stellar Lyman alpha emission flux that is absorbed as a function of the interstellar hydrogen column density and orbital phase. Typically, when N(H) is less than 10^{18} cm^{-2}, the absorbed fraction is less than 25%, and it varies with the orbital phase by less than 10%.

3. RESULTS

Figure 3 shows the light curves for the Lyman alpha, CII 1335, and CIV 1550 emission lines, normalized to their maximum values. The Lyman alpha fluxes were corrected for geocoronal emission and for interstellar absorption (assuming N(H)=10^{18} cm^{-2}). The FES counts (representing the V light curve) are plotted together with a synthetic visual (5500 Angstroms) light curve computed with the code kindly provided by Dr. S. M. Rucinski. This code was described by Rucinski (1973). Between orbital phases 0.0 and 0.5 the emission line and visual light curves are very similar (f/f(bol)=constant). However, the line fluxes (especially CIV) seem to be lower between the phases 0.5 and 0.0. If true, this indicates that the transition region on the phase 0.75 side of the system is fainter than that on the phase 0.25 side. However, these observations were made at higher radiation levels and are of poorer quality than those observed later, when the radiation was negligible.

The high-resolution spectrum SWP28625 obtained about a week later between phases 0 and 0.5 provides us with a means to verify our Lyman alpha correction procedures. The spectrum is shown in Figure 4. In this high-resolution spectrum the narrow geocoronal emission is clearly seen, mostly masking the underlying interstellar absorption. However, the broad stellar wings are visible. For comparison, a theoretical profile is shown. This profile was computed with N(H)=10^{18} cm^{-2} and a flux mean between phases 0.92 and 0.57, weighting the profiles of different phases with the low-resolution Lyman alpha fluxes (after the geocoronal subtraction). The total flux in the theoretical stellar emission profile (without interstellar absorption) is 17.2 10^{-12} erg s^{-1} cm^{-2}. This value is somewhat uncertain (+/-20%), since no actual fit with the observed wings was attempted. However, the fit is reasonable, and the total Lyman alpha flux used is quite compatible with the mean low-resolution flux between phases 0 and 0.5.
The total CII and Lyman alpha intensities of solar active regions are correlated, and a linear relation $F(\text{Lyman alpha}) = 25F(\text{CII})$ for a sample of active regions follows from Schrijver et al. (1986). We find for 44i Boo $F(\text{Lyman alpha}) = (18 \pm 6)F(\text{CII})$, quite consistent with the solar active region data. We note, however, that the absolute values of the surface fluxes in 44i Boo are much larger, indicating higher surface coverage of magnetic field than in solar plages. In the most intense solar active region studied by Schrijver et al. $F(\text{Lyman alpha}) = 2.5 \times 10^6 \text{ erg s}^{-1} \text{ cm}^{-2}$, compared with the mean value $6.5 \times 10^6 \text{ erg s}^{-1} \text{ cm}^{-2}$ for 44i Boo.

Fig. 4 The high-resolution Lyman alpha spectrum of 44i Boo obtained 6 July 1986, between orbital phases 0.92-0.57. The theoretical profile is shown by the dashed line. The geocoronal emission is clearly visible inside the broad stellar emission wings. The positions of the interstellar neutral hydrogen and deuterium are marked.

4. DISCUSSION AND SUMMARY

The symmetry of the high-resolution Lyman alpha profile and the lack of any clear rotational modulation of the line fluxes imply that both components of the 44i Bootis system must have similar chromospheres and transition regions. This should be expected, because both components have almost equal effective temperatures and apparently equal angular velocities. To a zeroth approximation, each component would therefore have equal "dynamo numbers".

The classical theory of contact binaries assumes "a common convective envelope" where both stars are embedded. However, more developed theories deviate from thermal equilibrium, producing quite unequal convective zones for the component stars (see for example Rahunen 1981 and 1982; Rahunen and Vilhu 1982). If the chromospheric and transition region line fluxes are indicative of the magnetic activity, then the dynamo power of the components should be equal, and the physical properties of the dynamo layers (such as temperature, density, rotation, differential rotation, turbulent velocities, etc.) should be equal as a consequence. However, as pointed by Vilhu and Heise (1986), because contact binaries are close to the observed saturation limits of all chromospheric and transition region indicators, this test is very insensitive to the dynamo-related parameters.

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MAPPING OF SURFACE ACTIVITY ON THE W UMA-TYPE SYSTEM VW CEPHEI

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ABSTRACT

Multifilter photometry of the W UMa-type contact binary VW Cep (P = 6.67 hr; G5V + KOV) in 1986/87 revealed large asymmetries in the light curves believed to be caused by large, cool starspot regions on the surface of the larger star. In April 1987 we observed VW Cep with IUE to study the chromospheres and transition regions of the components. During one complete orbital cycle 3 SWP and 4 LWP low dispersion spectra were obtained including and then excluding the suspected active region. For the first time, phase dependent TR line emission strengths were found, most notably CIV, which was 50% stronger when the spot region was most visible. These results could be important because VW Cep represents an extreme case for studying stellar dynamo theory and observations can play a crucial role in the understanding of magnetic fields and activity cycles in rapidly rotating solar-like stars.

Keywords: Cool Stars, W UMa Binaries, Starspots, Chromospheric Activity, Stellar Dynamos

1. INTRODUCTION

Observations of W UMa-type binaries with the IUE have shown that these stars are rich sources of ultraviolet emission. They generally have large surface fluxes of high temperature lines such as CII, CIV, NV, and SIV as well as moderate temperature (10^4 K) chromospheric emission lines of MgII, Lyα, C I, O I, and Si II. In analogy with the chromospherically active RS CVn stars, these line emissions are thought to arise from dynamo generated magnetic fields since these stars possess tidally enforced rapid rotation and deep convective zones, at least for the shorter period systems. However, because of their strong tidal interactions, components of W UMa systems should not possess significant differential rotation (both radial as well as latitudinal) which is believed to be an important component of stellar dynamo theory (Refs. 1, 2).

The light curves of most of the shorter period W UMa systems, of G to K spectral type, display markedly asymmetric light curves. Modeling of light curves using cool spotted regions can account for these asymmetries (Ref. 3). The presence of starspots on these stars is not unexpected because of their very short orbital and rotational periods. However, the W UMa-type stars are not as active as simple extrapolations of trends for detached binaries (the RS CVn stars) would indicate (Ref. 4). This could indicate a saturation of the dynamo mechanism in these stars.

2. PHOTOLOGY OF VW CEPHEI

VW Cep (HD 197433) is one of the brightest (Vmax = + 7.8 mag), best observed short period W UMa-type binaries. It consists of ~ G5V and ~ KOV components in contact with their Roche limiting surfaces. Photoelectric photometry has been carried out on this star since 1948. Since 1978, VW Cep has been monitored photoelectrically at Villanova University Observatory. These light curves were combined with others obtained over the same time interval and found to change systematically with time. During 1979-81 asymmetries are evident in the light curves with the brightness of maximum I (at 0.25P) and maximum II (at 0.75P) as well as minimum I (at 0.0P) and minimum II (at 0.50P) changing up to 0.07 mag (in yellow) with a characteristic period of ~ 155 ± 5 days. The light curves obtained during 1982-84 appear to be disturbed the least amount. Beginning in 1985, and continuing through 1987, the light curves are asymmetric with max I being ~ 0.06 mag brighter than max II. The long term behavior of the system is illustrated in Fig. 1 in which the differences between the brightness of the maxima at 0.25P and 0.75P for a given light curve are plotted against time in the sense [mag(max II) - mag(max I)]. This gives a rough measure of the asymmetry present in the light curves. A value of 0.0 for this quantity corresponds to a time when the two maxima of the light curve are equal while a negative number would indicate that max II is brighter than max I. As shown in the figure, the ~ 155 day periodicity of the light curve asymmetry found during 1979-81 was not present during 1985-87. In the lower portion Fig. 1, the mean light levels from the light curves are plotted. The mean light level was determined by averaging the system’s brightness at phases 0.0P, 0.25P, 0.50P, and 0.75P. As shown, the mean light level of VW Cep varies by ~ 0.06 mag with time. VW Cep was faintest during 1979/80 and 1986/87 and brightest during 1982-84. The asymmetries appear to be greatest when the system is the least luminous.

The apparent correlation between the mean brightness of the system and the size of the light curve asymmetries indicates that starspots...
are probably responsible for this behavior. Using the starspot model developed by Bradstreet (Ref. 3), we were able to reproduce the observed light curves with extended starspot regions on the surface of the larger, cooler star of the system. We were able to make a preliminary fit to the asymmetric light curve obtained during April 1987 shown in Fig. 2. The area of the two spots at this time was ~ 6% of the total surface area of the larger star, with a temperature of 450° ± 150 K cooler than the surrounding photosphere.

The ~ 155 day cyclic behavior observed during 1978-81 appears to arise from a small difference between the rotational period of the starspot region and the orbital period of the binary. The 155 day period is apparently the beat period between the orbital period and the rotational period of the photospheric region where the spots were located at this time. The migration of the spotted region around the surface of the cooler star produces the varying light levels of the maxima and minima of the light curve. At times, when the spots are small, such as in 1982-84, the asymmetries are smallest and the mean brightness of the system is greatest, and vice-versa as in 1979/80 and 1986/87. This apparent spot cycle produces the long-term variation in the mean light level of the binary as shown in Fig. 1.

3. IUE OBSERVATIONS OF VW CEPHEI

During 1986/87, the light curves of VW Cep were very asymmetric and the mean light level was about 0.10 mag fainter than observed during 1982-84. Because of this high level of surface activity we were granted, in April 1987, one USI discretionary shift to study the nature and location of the phenomena affecting the light curves. During one complete orbital cycle, 3 SWP and 4 LWP low dispersion spectra were obtained. The location of the spotted region was inferred from ground-based photometry. The SWP exposures were centered on the orbital phases 0.84P, 0.13P, and 0.60P. These phases were chosen in an attempt to include and then exclude the suspected active region. The LWP exposures were centered on phases 0.80P, 0.25P, 0.45P, and 0.75P. Fig. 3 shows a polar view of VW Cep illustrating the exposure intervals of the IUE spectra. The integrated emission line fluxes of C II (X1335) and C IV (X1550) are given below the SWP image numbers (in units of ergs cm\(^{-2}\) s\(^{-1}\) x 10\(^{-13}\)). The Mg II line fluxes are given below the LWP image numbers in the same units. The locations of the starspot regions obtained from modeling the light curve are also shown in the figure. Fig. 4 shows the SWP spectra of VW Cep obtained on 05 April 1987. The strongest emission features are identified in the figure. The top spectrum (SWP 30713) was taken when the starspots were most visible and displays the strongest emission features. The other two spectra were obtained when the spotted regions were only partially visible. For the first time, phase dependent variations in the TR line emissions were discovered, most notably C IV, which was 50% stronger when the spc regions were most visible. From the LWP observations there appears to be a 20% variation in the level of Mg II emission, but this occurred during secondary eclipse and, thus, may be due to the occultation of a localized emitting region in the chromosphere. Fig. 5 shows the possible phase dependent variations of the C IV and Mg II line emissions, plotted together with the ground-based light curve obtained during April 1987.
Figure 2. Red (X6600) light curve obtained in April 1987 at Villanova. The solid curve represents the theoretical light curve with starspots. The starspots are $450^\circ \pm 150^\circ$ K cooler than the surrounding photosphere and occupy an area ~6% that of the larger star.

Figure 3. Polar view of VW Cep illustrating the exposure intervals of the SWP spectra. The phase at which the LWP spectra were taken is also shown. Below the SWP image numbers is the line flux (in ergs cm$^{-2}$ s$^{-1}$) x 10$^{-13}$ of C II and C IV. The Mg II line fluxes are given below the LWP image numbers.

Figure 4. SWP spectra of VW Cep obtained 05 April 1987. The top spectrum (SWP 30713) was centered on 0.84P when the starspots were most visible. The middle spectrum (SWP 30714) was centered at 0.13P, and the bottom spectrum (SWP 30715) was centered at 0.60P. The insets in the upper righthand corners show representations of VW Cep at the appropriate phase of mid-exposure.
roughly coincide with the maximum C IV emission. However, the small number of spectra and their phase distribution are insufficient to determine unambiguously the association of the UV line emissions with the stellar regions defined by the starspots. We plan more observations of VW Cep with IUE during 1988 to test our results.

4. CONCLUSIONS

VW Cep seems to possess all of the common indications of enhanced solar activity that are expected from dynamo generated magnetic fields. The presence of starspots and a possible starspot cycle are inferred from the ground-based photometry. As this study shows there are strong chromospheric and transition region emissions which are indicators of enhanced stellar activity. Moreover, there appears to be a correlation between the visibility of the starspots and the strength of the transition region emissions in the sense expected if the spot forming regions and the transition region sites were physically related. However, the phase dependence of the transition region line emissions and the possible variation of Mg II emission needs to be confirmed with more observations.

The rapid rotation ($V_{rot} = 150 \text{ km s}^{-1}$) of VW Cep and deep convective layers of its components are in general accord with the high levels of surface activity inferred from the ultraviolet and ground-based observations. However, due to the strong tidal interactions between the two components, the other assumed necessary ingredient to most stellar dynamo theories - that of differential rotation - should be missing or at least substantially reduced in contact systems like VW Cep. Nonetheless, VW Cep and other W UMa-type binaries display levels of implied chromospheric and transition region activity that are among the greatest of solar-like stars. Perhaps extrapolations of the solar activity paradigm to these complex binaries are naive, missing some important mechanism which creates and sustains such large and long-lived active regions. During 1988 we have been granted time on the IUE satellite to secure more detailed ultraviolet observations of VW Cep and these observations should answer some of these questions (or possibly raise new ones) concerning the study of stellar activity and dynamo theory at extreme rotational velocities.

We wish to thank Dr. Yoji Kondo for granting us a discretionary shift with the IUE at a time when the target was most active. This work was partially supported under Grant #87-090 from NASA which is gratefully acknowledged.

5. REFERENCES


Figure 5. The yellow light curve of VW Cep obtained during April 1987 is shown in the top panel. The phases most affected by the starspots are indicated. The Mg II and C IV line fluxes are plotted versus phase in the lower panel.
Ultraviolet flares on II Peg

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Abstract: IUE observations of the RS CVn star II Peg in the upper chromospheric and transition regions lines MgiI, CIV and HeII in February 1983 shows evidence for flare activity. The electron pressure derived from the mean of two different line ratios produce good agreement between the allowed and intersystem lines in the differential emission measure curves. The total radiative losses from the chromosphere and transition region for the first flare on Feb. 2 is \(2.46 \times 10^{35} \text{ erg}\) and at least \(1.91 \times 10^{34} \text{ erg}\) for the flare on Feb. 4.

Key Words: flares - UV data - line ratio - electron pressure - differential emission measure

1 Introduction

II Peg (= HD 224085), spectral type K2 IV-V is a single-line spectroscopic binary with a photometric period of approximately 6.7 days. Based on the photometric variability, this star was first classified as a BY Dra-type variable, however a more detailed study by Rucinski (1977) concluded that it was probably an RS CVn-type star, although its companion has yet to be observed.

Rodono et al (1986,1987) and Byrne et al (1987) have discussed ultraviolet and optical data taken in 1981. The ultraviolet data indicated a phase modulation in the sense that the maximum ultraviolet emission was observed at the time of the minimum in the optical light curve. This was interpreted as a hot plage region overlying one of the inferred cool optical spots. However, a subsequent follow-up study in 1983 (Andrews et al 1988) did not show any large scale phase modulation in the ultraviolet, although several high points were observed. These were interpreted as flares. Here, we discuss these flares in detail deriving an estimate for the flare's electron pressure, volume and the required mechanical input to the chromosphere from the differential emission measure curves.

2 Data Reduction

The 1983 IUE data has been discussed in detail by Andrews et al. Here, we consider only the short wavelength spectra, reduction being through use of the STARLINK program DIPSO (Howarth and Maslen 1983). Andrews et al identified two flares, the first starting on 1 February 1983 at 23:34 UT and lasting until at least 05:36 UT on 2 February (observed in the IUE exposures SWP19165, SWP19167 & SWP19168), the second flare was on 4 February 1983 at 01:33 UT (observed in IUE exposure SWP19184). Line fluxes for the emission lines were derived from least-squares gaussian fits. The FWHM of the fitted lines were consistent with the instrumental width of 6 Å for low resolution SWP spectra. To derive line fluxes, Andrews et al used a summation procedure; this procedure give similar results for the strong unblended lines, however for partially blended lines such as CIII 1908 Å, the gaussian fits are superior. The factor used to convert to surface flux at the star was \(2.3 \times 10^{17}\) from Table 7 of Rodono et al 1986.

Fig. 1 shows the CIV doublet for the four flare spectra plus a mean quiescent spectrum derived from a mean of images SWP19187, SWP19192, SWP19202 and SWP19205 (see Andrews et al for dates and UT of these images).

3 Results

3.1 Electron Pressure

The electron density was derived through the line ratio technique, see for example Doyle et al 1980 or Dere and Mason (1981) for a discussion of this technique. Two different line ratios were used, (i) CIII 1176/CIII 1908 and (ii) SiIV 1400/CIII 1908. The CIII/CIII has been discussed in detail by Byrne et al (1987), where the ratio was calibrated using solar data. The CIII/CIII line ratio was from Doyle et al (1980). For the mean quiescent atmosphere we derived \(P_e = 6 \times 10^{14} \text{ cm}^{-3} \text{K}\) from both ratios, whereas for the three flare spectra on Feb. 1 & 2 (i.e. the quiescent fluxes have been subtracted from the line fits in SWP19165, SWP19167 and SWP19168), we derived \(P_e = 4 \times 10^{15} \text{ cm}^{-3} \text{K}\). (Note that the temperature of for-
nation of Si IV and C III was taken to be \( \log T_e = 4.8 \). Again the agreement between the derived pressures from the two different line ratios is very good. However, for the flare on Feb. 4 the agreement was not as good, a mean value from these two ratios would imply a slightly smaller pressure of \( 3 \times 10^{14} \text{ cm}^{-3} \text{K} \).

Figure 2: The differential emission measure (d.e.m.) curve for the flare 23:54 UT on Feb. 1 1983 on II Peg. Allowed lines are given by —, while inter-system lines are given by —. The electron pressure used for the flare d.e.m. curve was \( 4 \times 10^{15} \text{ cm}^{-3} \text{K} \). Note that the d.e.m. plotted here have not been multiplied by the derived filling factor.

3.2 differential emission measure

The differential emission measure (d.e.m.) curves were constructed as described in Byrne et al (1987) using the tabulation of flux versus pressure for a constant d.e.m. from Raymond and Doyle (1980). As an example of the fit we show in Fig. 2 the d.e.m. curve for the flare only observation at 23:54 UT on Feb. 1, assuming \( P_e = 4 \times 10^{15} \text{ cm}^{-3} \text{K} \). Note the good agreement between the allowed and inter-system lines, this implies that we have used the correct electron pressure. (Note that all the d.e.m. curves in Byrne et al (1987) should be divided by a constant factor of \( \pi \)). The flare d.e.m. curve of Fig. 2 should be considered only as a lower limit to the true d.e.m. as we have taken the flare emission as distributed over the total stellar surface. In the next section, we will attempt to estimate a filling factor.

3.3 flare volume — filling factor

Theflare volume may be estimated from the total luminosity of an optically thin line, provided the electron density and the various atomic parameters of the line are well known. For example the total power in an optically thin line is given by

\[
P = h\nu N_e C_{ij} N_i V
\]

where \( h\nu \) is the transition energy, \( N_e \) the electron density, \( C_{ij} \) the electron rate coefficient, \( N_i \) the upper level population and \( V \) the volume. Taking the parameters for C IV as in Byrne et al we derive \( V = 9.3 \times 10^{31} P/N_i^2 \) where \( P \) is the power of the C IV doublet in \( \text{erg s}^{-1} \). Taking the radius of II Peg as \( 2.8 R_\odot \) as in Rodono et al (1987), an electron density of \( 4 \times 10^{10} \text{ cm}^{-3} \) and the observed C IV flare flux at the Earth; we derive a volume of \( 2.9 \times 10^{30} \text{ cm}^3 \) for the flare only spectrum in IUE image SWP19165. The size of the second flare observed during image SWP19184 would be only slightly less due to the smaller C IV flux and the smaller electron density.

Assuming a semi-circular loop structure of height \( h \), radius \( \alpha h \), where \( \alpha \) is the ratio of the loop radius to loop height; the volume is given by \( \pi \alpha^2 h^3 \). Taking \( \alpha \) to be 0.1 - 0.2 as in the solar case, we derive a loop height of 2 - 3 \( 10^{10} \text{ cm} \). This would imply that the surface area of the flare is of the order of 0.001 of the stellar surface, therefore our flare d.e.m. curves are under estimated by the inverse of this factor.

3.4 mechanical energy

A lower limit to the mechanical energy input to the chromosphere, during both the flare and in the star's quiescent state, may be estimated by calculating the total radiative losses. The radiative losses per second per unit surface area over the temperature interval \( 4.3 \leq \log T_e \leq 5.4 \) can be calculated by multiplying the derived d.e.m. curve by the radiative loss function. As in Byrne et al we used the radiative loss function of Raymond et al (1976); this gives for the quiescent atmosphere of II Peg total losses of \( 4.27 \times 10^{6} \text{erg cm}^{-2} \text{s}^{-1} \) and \( 22.75 \times 10^{6}, 10.90 \times 10^{6}, 12.36 \times 10^{6} \) and \( 8.38 \times 10^{6} \text{erg cm}^{-2} \text{s}^{-1} \) for the flare only spectra in images SWP19165, SWP19167, SWP19184 and SWP19184 respectively. Note that these latter flare values may be under estimated by perhaps a factor of 1000, due to the filling factor (see section 3.3).
Again note that the values in Byrne et al. have been incorrectly multiplied by a factor of $r$, making the required correction we obtain a value of $5.4 \times 10^6 \text{ erg cm}^{-2} \text{s}^{-1}$ for the quiescent atmosphere in the 1981 data set, being slightly larger than the present value. This is because the mean quiescent fluxes used here are approximately 20% smaller than those used by Byrne et al.

Multiplying the above figure by the stellar surface area (i.e. since the emission measure is per unit surface area), we estimate that the total radiative energy over the temperature range $4.3 < \log T_e < 5.4$ is at least $1.49 \times 10^{34} \text{ erg}$ during the flare (i.e. we have assumed that the flare or flare events lasts from 23:54 UT on Feb. 1 to 05:36 UT on Feb. 2 and that the emission varies linearly between the measured points). This is an underestimate since we do not know when the flare ended, the next spectrum taken after 05:36 UT was SWP19174 (see Andrews et al.) at 22:38 UT on Feb. 2; this spectrum showed only a slight enhancement.

We can also estimate the total losses in the chromospheric line Mg II from Andrews et al., assuming the same time interval for the flare or flare events, this is $2.24 \times 10^{34} \text{ erg}$. However, the major radiative energy loss source in the chromosphere of these stars is Ly $\alpha$ (see Linsky et al. 1988, Panagi et al. 1988). From a flare observed by Linsky et al. in HR 1099, it was found that the radiative losses from Mg II $h & k$ was 0.3 that of Ly $\alpha$. Using this figure we would estimate that the total radiative losses from Ly $\alpha$ during the first flare to be $7.47 \times 10^{34} \text{ erg}$, giving a total radiative losses for the $4.0 < \log T_e < 5.4$ temperature range of $2.46 \times 10^{35} \text{ erg}$.

For the second flare on Feb. 4, we have only one 80 minute exposure. An SWP exposure taken 5 hrs. later showed no evidence for enhanced emission lines. To estimate the total radiative losses we have assumed that the flare lasted for only 80 minutes. This gives for $4.3 < \log T_e < 5.4$ temperature interval total radiative losses of $1.91 \times 10^{34} \text{ erg}$. An LWR exposure taken immediately after the SWP exposure showed no enhancement; however based on the first flare the Mg II $h & k$ and Ly $\alpha$ contribution could be as much as 60% of the transition region radiative losses.

4 Discussion

Previous observations with IUE (Rodono et al. 1987, Byrne et al. 1987) have demonstrated the occurrence of discrete compact active regions, bright in transition region emission lines. These compact active regions lay close to the major spot group, although not directly over the spot. In a study of 1981, 1983 and 1985 ultraviolet data, Doyle (1988) found not only evidence for the presence of long-lived optical spot groups on one hemisphere of II Peg but also a corresponding long-lived plage region. The flares studied here occurred on this active hemisphere. The electron pressure derived from the mean of two different line ratios was approximately a factor of seven greater in the flaring atmosphere than in the quiescent atmosphere. These pressures produced good agreement between the allowed and intersystem lines in the differential emission measure curves in both the quiescent and flaring atmosphere. The total radiative losses from the chromosphere and transition region (i.e. over the temperature range $4.3 < \log T_e < 5.4$) for the first flare on Feb. 2 is $2.46 \times 10^{35} \text{ erg}$ and at least $1.91 \times 10^{34} \text{ erg}$ for the flare on Feb. 4.

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CHROMOSPHERIC MASS MOTIONS DURING A FLARE ON UV CETI

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ABSTRACT

Simultaneous optical and IUE observations of a flare on UV Ceti in 1980 are reported. The IUE spectra show only slight increase of C IV line emission. The optical spectrophotometric observations show, from Balmer line profiles, some turbulent broadening in quiescent and flare spectra, and downward-directed flow (of 100 km s\(^{-1}\)) during the flare. The latter is particularly reminiscent of solar flares, and probably arises from the formation of a ‘chromospheric condensation’, as modelled for solar flares.

1. INTRODUCTION

UV Ceti (=L726-8B) is the prototype dMe flare star, and its optical flaring activity has been known for forty years. The flaring rate is about three \(\Delta U > 1^m\) flares per hour (Kunkel 1973), with the flare light-curve generally showing a strong initial impulsive component in which continuum emission is strong and a slower component immediately following, in which the Balmer and other optical lines are strong.

In this work, we report optical spectrophotometric and photometric observations of UV Ceti during quiescent and flaring states in 1980, with simultaneous far-ultraviolet low-resolution observations with IUE. A comparison with solar flares is made.

2. THE OBSERVATIONS

The optical observations were made on 1980 Sept. 17, using telescopes at the South African Astronomical Observatory. The SAAO 0.5m reflector was used for the \(UBV\) photometry, and the spectrophotometry obtained with the 1.9m reflector with Cassegrain spectograph and Image Photon-Counting System.

The latter covered the range 3800–5100 Å with a resolution (FWHM) of 1.0 Å, determined from copper-argon arc exposures. Photometric observations were made from about 21\(^h\)15\(^m\) till 03\(^h\)00\(^m\) on Sept. 18, with a few gaps owing to cloud. Flare-like increases occurred at 22\(^h\)22\(^m\).5 (\(\Delta U = 2^m.7\)), 00\(^h\)12\(^m\) (\(\Delta U = 1^m.2\)), 02\(^h\)05\(^m\) (\(\Delta U = 1^m.0\)) and 02\(^h\)20\(^m\) (\(\Delta U = 3^m.3\)). The spectrophotometric observations were made in exposures of between six and 32 minutes from 21\(^h\)36\(^m\) to 00\(^h\)14\(^m\), with good coverage of the first flare.

The main features of the spectra obtained are emission lines of the Balmer series (H\(\beta\)–H\(\delta\)) and Ca II H and K with a continuum having TiO absorption bands; the Ca II H and K lines are unresolved. All the emission lines show enhancement at the time of the 22\(^h\)22\(^m\).5 flare. Detailed fits to the emission-line profiles were made to determine their widths and profiles. Single-Gaussian fits were found to be adequate for all lines except those in the flare exposure, for which two components were found necessary. Figure 1 is a plot of the flux of each emission line normalised to its average quiescent flux.

The profiles are significantly broader than instrumental, a typical width for H\(\beta\), for example, being 1.43 Å. On the assumption of Gaussian shapes for both instrumental and intrinsic stellar profiles, the H\(\beta\) intrinsic FWHM works out to be 1 Å. The H\(\beta\) and H\(\gamma\) lines in the flare exposure have significant red-wing excesses. These are depicted in Figure 2 (histograms), in which the two-Gaussian fit (curve) is also shown. These fits were achieved by assuming the red-wing emission to be a separate component with width equal to the main, undisplaced component. For both H\(\beta\) and H\(\gamma\), the peak of the secondary is 2.0 ± 0.1 Å to the red of the undisplaced component.

The optical observations were made on 1980 Sept. 17 and (with no optical coverage) Sept. 19. Figure 1 shows the durations of some of the exposures, which were made in low resolution with the short-SWP (LWR) cameras. The SWP images show strong H\,I Lyman \(\alpha\) emission, mostly geocoronal in origin, and weak C IV emission at 15550 Å; the LWR image shows Mg II (32800 Å) and very weak Fe II (26000 Å) emission. One of the exposures (SWP10169L) coincides with the optical flare, with peak time at 22\(^h\)22\(^m\).5. Despite the strength of the flare, there is only marginal enhancement of the C IV line feature over an exposure immediately before the flare (2.4 ± 0.4) \times 10\(^{-13}\) erg cm\(^{-2}\) s\(^{-1}\)).
3. DISCUSSION

The observed Balmer decrements (line intensities) may be compared with theory, though the physical insight into the conditions within the quiescent or flare atmosphere is rather limited. Cram and Mullan (1979) have calculated a grid of dMe star model atmospheres, predicting $H\alpha$, $H\beta$ and $H\gamma$ equivalent widths and line profiles. One of the parameters altered is the temperature gradient in the stellar chromosphere; as this is increased, the Balmer lines turn from absorption to emission lines. Our observed $H\beta$ and $H\gamma$ equivalent widths for the quiescent star (14 Å and 26 Å) are intermediate between their models 6 and 7 (having very high temperature gradients); for the flare itself, the values (23 Å and 28 Å) indicate a still higher temperature gradient. For these models, Cram and Mullan predict that the $H\alpha$ line (maybe others also) has an emission profile ~20 Å wide with central reversal. Unfortunately, with no $H\alpha$ observations, we can neither confirm nor deny this.

Values for the Balmer decrements including higher-n lines from such model-atmosphere calculations would prove very useful. Meanwhile, one can compare with the recombination theory of Seaton (1959) and Pengelly (1964) appropriate to planetary-nebula densities. Our observed Balmer decrements for $H\beta/H\gamma/H\delta/H\epsilon/H\delta$ for averaged quiescent spectra are 2.37/1.0/0.58/0.20/0.15, for the flare exposure 2.60/1.0/0.69/0.47/0.42. They compare remarkably well with the values of, e.g., Pengelly (2.11/1.0/0.55/0.23/0.16), though of course the expected flare densities are much larger than those in planetary nebulae.

The observed line widths indicate some turbulence, as they are wider than thermal Doppler widths convolved with Stark Broadening for densities of up to $\sim 10^{14}$ cm$^{-3}$. The most probable turbulent velocities from the $H\beta$ line widths are 35 km s$^{-1}$ (pre-flare), 39 km s$^{-1}$ (flare) and 31 km s$^{-1}$ (post-flare), with errors of about ±0.5 km s$^{-1}$.

The $H\beta$ and $H\gamma$ red-wing emission can be explained by a directed flow with velocity 100 km s$^{-1}$. This is very similar to what is seen in solar flares. Thus, Ichimoto and Kurokawa (1984) see enhanced red-wing emission in early stages of solar flares, with downward velocities of 100 km s$^{-1}$ initially, decreasing to 40 km s$^{-1}$ within a minute. This is explained by Canfield (1976) and others in detailed modelling of the solar-flare impulsive stage.

There is, in this picture, intense heating of the solar chromosphere by downward-moving electrons accelerated in the corona, leading to the ablation of the top layers of the chromosphere to produce soft X-ray-emitting material forced into the corona; simultaneously there is a downward-moving compression of the remaining chromospheric layers to produce a 'chromospheric condensation', giving rise to red-wing Balmer line excess. This would appear to fit the pattern of the present observations of this flare on UV Ceti.
Spectrophotometric observations of Balmer lines during a flare on UV Ceti show correspondence with dMe stars model atmosphere calculations with very high temperature gradient. The line widths indicate some turbulence during quiescence and flare activity, with most probable turbulent velocities of 30–40 km s⁻¹. There is, in addition, a red wing excess to the Hα and Hβ lines during the flare observed, explicable by a 100 km s⁻¹ downward-directed flow. This is consistent with solar-flare observations, and flare models which predict the presence of a downward-moving chromospheric condensation. Despite the strength of the flare, only a slight increase of C IV line emission was indicated by the IUE spectra.

The ratio of the emission line fluxes for the C II and C IV lines in the lower transition regions (3 × 10^4 < T < 10^5 K) between stellar chromospheres and transition layers depends mainly on the temperature gradient in the line emitting regions which can therefore be determined from this line ratio. The temperature gradient is determined by the equilibrium between energy input and energy loss. From the observed temperature gradient we can therefore determine the temperature dependence of the energy input, which is expected to be different for different energy input mechanisms. We study the flux ratios of the C II to C IV emission line fluxes in order to obtain information about the energy input mechanism.

Key Words: Transition layer, heating, Emission lines, T Tauri stars.

Theoretical Background

We follow the derivations by Bohm-Vitense (Ref. 1). We assume that the energy input \( E_{\text{in}} \) per cm\(^2\) and sec is due to the damping of some mechanical energy flux \( F_\lambda \). This means

\[
E_{\text{in}} = \frac{d F_m}{dh} = \frac{F_m}{\lambda},
\]

where \( \lambda \) is the damping length. Using \( T \) as the independent variable such that the gas pressure \( P_g = P_g(T) \) we can express a possible dependence of the damping length on \( P_g \) and \( T \) as a dependence on \( T \) only. We write

\[
\lambda = \lambda_0 \cdot T^\alpha.
\]

\( \alpha \) is a parameter which can be determined from the emission line fluxes.

The energy input is balanced by radiative energy losses \( E_{\text{rad}} \) per cm\(^3\) sec\(^{-1} \) which can be described by

\[
E_{\text{rad}} = E_{\text{los}} = n_e^2 \cdot f(T)
\]

where \( f(T) \) has been calculated by many authors for solar element abundances (see Rosner, Tucker, and Viirva 1978, (Ref. 2)). It can be approximated by

\[
f(T) = B \cdot T^\beta
\]

where for 30,000 K < T < 1.2 × 10^5 K the \( \beta \approx 1.9 \pm 0.1 \) and \( B \) is a constant.

The energy equilibrium then requires

\[
\begin{align*}
\frac{d n_e^2 \cdot f(T)}{dh} &= P_g^2 \cdot B \cdot T^\beta - \frac{F_m}{\lambda_0},
\end{align*}
\]

\( T^\beta \frac{d n_e^2}{dh} = \frac{F_m}{\lambda_0} \cdot B \cdot P_g^2 \) (4)

The electron pressure \( P_e \) is determined by the hydrostatic equilibrium equation which for fully ionized gases means

\[
\frac{d \ln P_g^2}{dh} = \frac{2}{H} dh \quad \text{with} \quad H = \frac{R_g \cdot T}{\mu_{\text{eff}}},
\]

where \( R_g \) = gas constant, \( \mu \) = mean atomic weight, \( \mu_{\text{eff}} \) = effective gravitational acceleration. With

\[
\frac{d \ln P_g^2}{dh} = \frac{1}{H} dh
\]

we find for the temperature gradient

\[
(\beta - 2 + \alpha) \cdot \frac{d \ln T}{dh} = \frac{2}{H} \frac{d \ln F_m}{dh} - \frac{1}{H} \frac{2}{\lambda_0} \frac{d h}{dh}
\]

and

\[
\frac{d \ln T}{dh} = (\beta - 2 + \alpha) \frac{2}{H} \frac{1}{\lambda(T)}
\]

If for a given temperature we can determine \( d \ln T \), we can determine \( \alpha \), which describes the temperature dependence of the damping length.

For different heating mechanisms we expect different values of \( \alpha \) (Ref. 2). The determination of \( \alpha \) for different stars therefore tells us whether different heating mechanisms work for different stars. Finding the same \( \alpha \) for all stars means that the same heating mechanism is working for all stars.

Method of Analysis

In the following we are considering only layers with 30,000 K < T < 1.2 × 10^5 K, i.e., layers for which equation (3) holds with \( \beta \approx 1.9 \pm 0.1 \).
The surface flux $F_1$ of optically thin emission lines is given by

$$F_1 = C(L,T)A(e) \int_{z_1}^{z_2} u^2 dh \ln T$$

where $C(L,T)$ are determined by the collisional excitation rates for each line, $A(e)$ is the abundance of the line emitting element. Using average values for the integrand and using equation (9a) we find

$$E_m(T) = \frac{1}{k^2} \left( \frac{a + \alpha - 1}{2} \right) \ln^2 \frac{T}{T_1}$$

The ratio of the observed emission line fluxes $f_1$ equal the ratios of the surface fluxes $F_1$, and are for the $C$ II and $C$ IV lines

$$\frac{f_1(C\emissionline{II})}{f_1(C\emissionline{IV})} = \frac{C(1335 \AA, T_1)}{C(1535 \AA, T_2)} \frac{E_m(C\emissionline{II})}{E_m(C\emissionline{IV})} \frac{\varphi(T_1)}{\varphi(T_2)}$$

In figures 1-3 we show the observed flux ratios $RC$ for different groups of stars. The observational error for the flux ratio is expected to be at least 50%, or $\Delta \log RC \approx \pm 0.2$ and more for weak lines.

[Figure 1: The line flux ratio of the carbon lines is shown as a function of the V-R colors for the stars studied by Ayres et al. The different symbols indicate different types of stars as explained in the figure. The RS CVn stars and the normal stars occur in the same region of the diagram. For 56 Peg at the UV emission lines originate mainly in a hot disk.]

[Figure 2: For the stars studied by Simon et al. the line flux ratio of the carbon lines is shown as a function of age of the stars. The age of the Hyades stars is probably smaller than used here, as indicated by the arrows. The different symbols refer to different types of stars as explained in the figure. Peculiar stars with abnormally low or high flux ratios are given by name.]
In figure 2 we show the results for main sequence G stars with different ages studied by Simon, Herbig and Boesgard (1985, Ref. 5). There is no obvious dependence of RC on age either, except for the somewhat smaller RC for a group of stars with ages around 10⁶ years which again seem to show excess C IV emission. We suspect that circumstellar emission enhances the C IV line flux, though for these stars we cannot exclude that a different heating mechanism may contribute to the heating of the lower transition region. For all the other stars with log RC = -0.1 ± 0.2 a value of \( f + \alpha - 1 = 1.3 ± 0.3 \) is found, which means \( \alpha \approx 0.4 ± 0.3 \) if \( f = 1.2 \).

**Figure 3.** The carbon line flux ratios are shown as a function of age for the T Tauri stars studied by Simon et al. The line flux ratio is generally lower for the T Tauri stars than for the normal giants and main sequence stars. They show a large scatter.

In figure 3 we show the RC values for T Tauri stars according to Simon, Herbig and Boesgard (Ref. 5). The points scatter all over the diagram. The C II and C IV emission lines are not due mainly to a transition region formed by the same heating mechanism as for nearly all other stars. This conclusion is in agreement with the one found by Simon, Herbig and Boesgard but derived from very different arguments. We suspect that circumstellar emission, possibly due to shocks, gives a major contribution to the emission line fluxes for the T Tauri stars.

4. SUMMARY

From the observed constant (within the limits of observational error) ratio of the emission line fluxes of the C II (1335 Å) and C IV (1550 Å) lines we conclude that the temperature gradients in the lower transition layers are similar for the large majority of stars independently of T eff, L and degree of activity. This means that the temperature dependence of the damping length for the mechanical flux must be the same for all these stars. Since for different kinds of mechanical fluxes the dependence of the damping length on gas pressure and temperature is quite different (Ref. 2) we conclude that the same heating mechanism must be responsible for the heating of all the lower transition layers of these stars, regardless of their chromospheric activity. Only the amount of mechanical flux changes.

The T Tauri stars are exceptions. For these stars the emission lines are probably mainly due to circumstellar material.

5. REFERENCES


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TRANSITION REGIONS OF dM STARS

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ABSTRACT

We have observed weak upper-chromospheric and transition region (TR) emission from two dM stars (G1784 and G1825) using deep IUE SWF exposures. In addition to the usual TR lines, Lyα fluxes for the two stars were also determined for the first time. In this paper we discuss the relative importance of Lyα and MgII as chromospheric coolants in the M dwarfs and the status of the X-ray/HeII(1640Å) relationship in the light of these results.

Key words: Late-type Stars - Flare Stars - Stellar Chromospheres

1. INTRODUCTION

Most of the work carried out on M dwarfs with IUE has concentrated on the most active stars i.e. the dMe or Hα-emission stars. Attention has recently been focused on the less active dM or Hα-absorption stars. Cram and Mullan (1979) and Cram and Giampapa (1987) pointed out that the presence of Balmer absorption is indicative of the presence of a stellar photosphere of appreciable density in the K and M dwarfs, since the photospheric radiation field alone is not enough to populate the third and higher levels of the hydrogen atom to any significant extent. Therefore significant amounts of mechanical energy can be deposited in the atmospheres of even the Balmer absorption M dwarfs (dM's).

Estimates of the chromospheric radiative loss rates from these stars, based on MgII h & k and CaII K & H fluxes, lead to a similar conclusion i.e. that there exist significant chromospheres in dM's and that the chromospheric heating rates are about an order of magnitude lower than in the dMe stars (Byrne et al. 1980, Byrne et al. 1985).

Byrne (1981) demonstrated that, in the case of G1825, even a Balmer absorption star is capable of producing sizeable optical flares. Byrne et al. (1985) found the same result for a second dM star, G1229. Their overall flare energy budget is very much smaller than those of the most active dMe stars however. Since then other examples of this type of behaviour have been reported (Doyle and Byrne 1986; Doyle et al. 1986).

2. OBSERVATIONS AND RESULTS

Three IUE spectra were obtained for each of the two stars, one SWP exposure of relatively short duration (~30 min) to avoid saturating the stellar Lyα, one deep SWP exposure (~4-6 hr) to detect the transition region lines and finally one LHP exposure (23 min) to record the MgII flux. Obviously Lyα is saturated in the deeper SWP exposure.

The spectra were extracted from the raw images using the IUEED computer program (Giddings, 1983) on the UK STARLINK computer network (Bromage, 1984). Considerable care was taken with the deep SWP images since the lines, with the exception of Lyα, were very weak. Each raw image was first examined on an image display and "hot" pixels or cosmic ray hits identified so that the extraction process would not be affected by them. The final spectra were smoothed with a gaussian filter of PWHM approx. 2.5 Å to reduce noise. This is still well below the nominal resolution of the IUE spectrograph in its low resolution mode i.e. approx. 4.2 Å (Bianchi et al. 1981).

The extraction of Lyα deserves special mention since procedures for achieving this are far from standard. The difficulty in extracting Lyα arises from the geocorona. This acts as an extended source which completely fills the aperture of the spectrograph. Our short SWP exposures were taken so as to avoid saturating both the geocoronal and stellar Lyα. This was necessary since the signals are additive. The geometry of the entrance aperture
have included the surface line fluxes from the dMe stars G1285 (YZ CMi), taken from Doyle et al. of typical dMe stars. To aid in this comparison we their radiative losses are substantially below those Cousins (1980), transformed to the Johnson derive line surface fluxes. We have used the fluxes were taken from Ayres et al, (1983), the MgII cooling rates entered in Table 1.

quiet Sun MgII surface fluxes have been derived from the data in Gemare et al. (1981).

to a rectangle with two semicircles, one at either end. During the short SWP exposure the star was offset slightly from the centre of the aperture in a direction perpendicular to the dispersion. It was then possible to extract the image of the star plus geocorona along with an adjacent portion of the image which contained the geocorona only and then derive the stellar Lyα alone by subtraction. This procedure was checked using exposures on the geocorona only, taken as part of a later programme (Doyle et al. 1988). These images were reduced at the same positions as the stellar images. The differences in the derived geocoronal fluxes at the two positions were always less than 5%.

Weak transition region and upper chromospheric fluxes were recorded from both stars and fluxes derived by fitting gaussian functions, which were fixed in width at the instrumental width (FWHM = 4.5 Å) but the central wavelengths were allowed to vary.

3. DISCUSSION

To intercompare stars of various levels of activity and spectral type, it is necessary to derive line surface fluxes. We have used the relationship between radius and (V−R) colour given in Byrne et al. (1985) with the (V−R)0.0 photometry of Cousins (1980), transformed to the Johnson system, and distances from Gliese (1969) to derive the stellar radii. The resulting surface fluxes are entered in Table 1.

3.1 Chromospheric and Transition Region radiative cooling rates

The transition region and chromospheric line surface fluxes for G1784 and G1825 confirm that their radiative losses are substantially below those of typical dMe stars. To aid in this comparison we have included the surface line fluxes from the dMe stars G1285 (YZ CMi), taken from Doyle et al. (1988), and G1803 (AU Mic) in Table 1. The G1803 Lyα fluxes were taken from Byrne et al. (1983), the MgII fluxes from Byrne et al. (1980) and the remainder from Butler et al. (1981). Also included for comparison are the quiet Sun surface fluxes taken from Mount et al. (1980).

Examination of Table 1 reveals the following. First, the mean surface fluxes of the two dM stars are remarkably similar, both to one another and to the quiet Sun. In both stars the mean surface fluxes tend to be slightly less than the quiet Sun values. This is true from the chromosphere (SiII) to the mid-transition region (CII, CIV) (HeI is a well-known exception, see below) and including Lyα. Furthermore, the ratio of the stellar line surface fluxes to those of the quiet Sun are approximately constant with the temperature of formation of the ion. This is in contrast to the two dMe stars, G1285 and G1803, where the higher temperature line surface fluxes are proportionately much more enhanced relative to the quiet Sun. The dramatic exception to this behaviour is the MgII doublet. It is much stronger in the Sun than in either the dM or the dMe stars.

Second, MgII makes a relatively greater contribution to chromospheric cooling in the dM stars than does Lyα. In contrast to the two dMe stars, where Lyα is greater. Lyα surface fluxes were also found to be greater than MgII in the RS CVn star, 11 Peg by Panagi et al. (1988) but Weiler et al. (1977) and Ballunas et al. (1984) found the reverse for V11 Tau (HR1099) and Lambda And, respectively.

Third, the dM star surface fluxes are very similar to those reported by Fernandez-Figueroa et al. (1981) for the dK5 star, 61 Cyg A, and by Linsky et al. (1982) for its companion, the dK7 star, 61 Cyg B. Indeed, the mid-transition region line surface fluxes (CII, CIV) for G1825 are identical, within observational error, with those for 61 Cyg A.

3.2 Coronal radiative cooling rates

X-ray observations of G1285, G1803 and G1825 are available (Bookbinder, 1985). These are given in Table 1 both as fluxes at Earth and average surface fluxes at the star itself. Also included in Table 1 are similar figures for the quiet Sun. The latter have been derived by combining the quiet Sun differential emission measure of Raymond and Doyle (1981) with the radiative loss functions of Raymond et al. (1976), using the power law approximations of Rosner et al. (1976).

The most striking thing about the X-ray surface fluxes is that, while G1285's transition region fluxes are comparable to solar values, its X-ray emission per unit surface area is about a factor of 10 higher. Thus, while there appears to be very little difference in the emission measures up to the mid-transition region between the quiet Sun and the dMe stars, this changes dramatically as we move to coronal temperatures. It should be noted that the dMe stars' X-ray surface fluxes are factors of approximately 60 (G1285) and 600 (G1803) higher yet again. This conclusion is based on one star since there is, at present, no X-ray flux for G1784. An X-ray flux is available for G1229 however and it is comparable to that for G1285.

The difference in the emission measures of G1285 and the quiet Sun at the coronal level can be accounted for by the following scenario. Since they exist on the Sun and since we have observed optical flares on G1285, it is reasonable to assume that
active regions exist on the dM stars. If the surface flux of these active regions approximates to that of the mean global surface flux of the most active flare stars, such as BY Dra and AU Mic, then a 0.02% surface coverage of G1825 is sufficient to account for the observed excess in X-rays. This arises because, while mid-transition region line surface fluxes are enhanced by factors of order 50 in the flare stars over the quiet Sun, the mean X-ray surface flux may be enhanced by factors of ~5000 (cf. Table 1). Thus the quoted surface coverage by active regions would increase the mean global surface flux in lines such as CIV by only ~10% over that for a completely "quiet" star while the X-ray emission would increase by a factor of ~10.

3.3 The HeI(1640Å) line

As remarked above, the surface flux of the observed SWP lines are less than solar except HeII. The formation of this line has been widely discussed both in the Sun (Zirin, 1976; Kohl, 1977) and in stars (Hartmann et al. 1979; Rego et al. 1983). The evidence appears to favour a substantial contribution by recombination following ionization by coronal X-rays in the most active stars. Hartmann et al. first suggested a relationship between coronal X-ray flux, $F_x$, and HeII(1640Å) flux, $F_{\text{HeII}}$, of the form

$$\log(F_x) = \log(F_{\text{HeII}}) + c,$$  \hspace{1cm} (3.1)

with a value for $c$ of about 1.70, based on IUE observations of two late-type active dwarf stars. Rego et al. extended the sample to giants as well as dwarfs, and over a wider range of temperatures. They proposed two relationships, one an improvement on Hartmann et al. which may be written as

$$\log(F_x) = 1.95 + 0.94 \log(F_{\text{HeII}}).$$  \hspace{1cm} (3.2)

and another, relating HeII and CIV(1548/51Å) flux, which may be combined with the above to yield

$$\log(F_x) = 1.03 + 1.06 \log(F_{\text{CIV}}).$$  \hspace{1cm} (3.3)

We have tested these relationships using our new data for G1825 as well as IUE and EINSTEIN data obtained from the literature. Our sample has been limited to M dwarfs to make it more homogeneous than that of Rego et al. The data used will be found in Byrne and Doyle (1988) and they are plotted in Fig. 1. It is clear that there is a tight relationship between X-ray flux and both CIV and HeII(1640Å) fluxes in the M dwarfs. Linear regressions yield the following mean relationships.

$$\log(F_x) = 0.87 + 1.04 \log(F_{\text{HeII}}),$$  \hspace{1cm} (3.4)

with a correlation coefficient of 0.96, and

$$\log(F_x) = -0.97 + 1.33 \log(F_{\text{CIV}}),$$  \hspace{1cm} (3.5)

with a correlation coefficient of 0.97.

Eqs. (3.4) and (3.5) differ fairly significantly from (3.2) and (3.3). We note that the $F_x/F_{\text{HeII}}$ relationship is tight with AU Mic and G1825 standing out more than the rest. AU Mic is an exceptional dMe star in other respects. Generally, however, Fig. 1 and Eq. (3.4) suggest that HeII is a good indicator of X-ray flux at least among the M dwarfs.

By way of contrast to its position relative to the mean $F_x/F_{\text{HeII}}$ line G1825 lies very close to the mean $F_x/F_{\text{CIV}}$ relationship. The deviation from the mean HeII relationship may arise from the increased effect of the blended HeII(1640Å) line as we go to weaker X-ray emitters. Both, the other stars in this part of the $F_x/F_{\text{HeII}}$ diagram are of much later type, and so have smaller surface areas (UV Ceti is of spectral type dM5.5e and Prox Cen is dM6e). Therefore, although their X-ray flux is low, the X-ray surface intensity is high. Accordingly we would expect the recombination contribution to the HeII flux to be higher in UV Ceti and Prox Cen. This result is in keeping with the suggestions of previous authors.

3.4 Rotation periods

Byrne et al. (1984) derived a relationship for X-ray flux and period which results in a period of 21 days for G1825. It should be noted however, that this relationship is very poorly defined for periods longer than about 10 days.
If, however, we use the data of Skumanich and McGregor (1986) to derive a relationship between CIV flux, normalized to bolometric luminosity, and period then we derive periods for both stars close to 40 ± 12 days, close to the prediction from the MgII fluxes. Good direct measurements of the periods of rotation of the two stars (by, for instance, Call or spot modulation) would do a great deal to clarify the matter. These observations are planned in the near future.

REFERENCES

TRANSITION REGION FLUXES IN A-F DWARFS:
BASAL FLUXES AND DYNAMO ACTIVITY

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ABSTRACT

We report analysis of the transition region spectra of a sample of 57 late A and early F dwarfs and subgiants. The emission line fluxes are uniformly strong in the early F stars, and drop off rapidly among the late A stars. The basal flux level in the F stars is consistent with an extrapolation of that observed among the G stars, while the magnetic component displays the same flux-flux relations seen among the solar-like stars. Despite the steep decrease in transition region emission flux for B-V<0.28, C II emission is detected in a Aql (B-V=0.22). The dropoff in emission is inconsistent with models of the mechanically generated acoustic flux available. We conclude that, although the non-magnetic basal heating is an increasingly important source of atmospheric heating among the early F stars, magnetic heating occurs in any star which has a sufficiently thick convective zone to generate acoustic heating.

Keywords: Transition Regions, Convection, F stars, A stars

1. INTRODUCTION

Stellar magnetic activity is a ubiquitous property of stars on the cool side of the H-R diagram (Ref. 1). The cool stars have deep convective envelopes in which the interaction of rotation and convection are thought to generate magnetic fields through the dynamo mechanism. On the main sequence the transition between the hot and the cool stars – in terms of activity – occurs in the late-A or early F type stars (Ref. 2). Theory predicts that stars hotter than B-V>0.30 do not have well-developed convective envelopes. These stars should not be able to maintain convectively-driven dynamos, nor should convectively generated noise be available to host acoustic waves. The study of the early F and late A stars on and near the main sequence, where this transition occurs, may show how the atmospheric heating depends on convection zone parameters.

Walter and Linsky (Ref. 3) reported on the initial results of this investigation. Wolff, Boesgaard, and Simon (Ref. 4) discussed activity in the F dwarfs based on observations of the C IV λ1550Å and He I λ5876Å lines. Both groups show that:

- All early F dwarfs exhibit strong transition region emission, with C II and C IV surface fluxes over 10^5 erg cm^{-2}s^{-1}.
- The observed transition region flux actually increases with decreasing B-V, as the thickness of the convective envelope decreases.
- There is remarkably little scatter in the surface fluxes among the early F dwarfs (.3<B-V<.42), while the cooler F dwarfs exhibit solar-like rotation-activity correlations.

X-ray observations (Refs. 5 and 6) showed similar results, with all early F dwarfs being detected at essentially the same surface flux. F stars with B-V>0.45 clearly exhibit a rotation-activity correlation, while the hotter stars do not. Stars hotter that B-V<0.30 are not strong X-ray sources.

Walter and Schrijver (Ref. 7) show that upon subtraction of appropriate basal fluxes from the total observed emission flux, the remaining emission fluxes (the excess flux) exhibit flux-flux correlations similar to those seen in cooler stars (cf. Ref 8.). The basal flux component may well be due to heating of the atmosphere by acoustic waves, while the rotation-activity and flux-flux correlations of the non-basal component suggest that it is due to magnetic processes similar to those observed on the Sun.

In this paper we concentrate on the behavior of the transition region fluxes in the late A stars, where the convection zone thickness becomes small.

2. OBSERVATIONS AND ANALYSIS

The observational data consist of deep SWP-LO observations of 57 late A and early F stars (0.21≤B-V≤0.53). The stars are, in general, close to the ZAMS (Fig. 1), based on Strongren uvby' photometry (Ref. 9). None exhibit significant reddening.
The observations were obtained during programs CC'DT, AFFJL, AFGJL, and ADFW, with a minority of observations from the IUE archives. The spectra were well exposed in order to bring up the relatively weak transition region lines, at the expense of greatly overexposing the photospheric continuum background of about 1600Å (Ref. 3). Emission line fluxes are measured above a quadratic background fit through the neighboring pseudo-continuum (strongly affected by scattered light in these stars) after smoothing the data with a Fourier filter. Upper limits are deduced from the magnitude of the largest noise feature near the location of the line of interest. Surface areas are computed using the Barnes-Evans relation.

The stars detected in C II at B-V=0.25 are HD25052 and HD90132. The former is a strong X-ray source, a Hyd., and a binary with a G dwarf. The latter is an apparently single AS dwarf. Simon and Landsman (Ref. 12) show that 53 Tan (B-V=0.26) also exhibits strong C II emission.

3. AQUILAE AND THE HOTTEST COOL STARS

We have obtained deep SWP-LO observations of 8 stars with 0.21≤B-V≤0.27. Three of these yielded detections of C II λ1335Å, while the rest yielded significant upper limits. There have been few reports of solar-like activity (including transition region and X-ray emission and He I absorption) in stars hotter than B-V=0.29. One exception is α Aql (B-V=0.22), which has been detected as an X-ray source (Ref. 10), and in H I Lyα (Ref. 11). We obtained 3 deep trailed SWP-LO exposures over an interval of 10 months. The coadded spectrum, shown in Fig. 3, shows likely emission above the local continuum at wavelengths consistent with identification with C II λ1335Å and Si IV λ1400Å. These emission features are visible in the individual spectra. The C II emission feature is enhanced upon subtraction of a template A7 dwarf star composed of 2 stars from our sample with B-V=0.21 and 0.22. The ratio of C II to X-ray surface flux is comparable to that observed among the early F dwarfs. For these reasons we are confident that the identification of C II emission in α Aql is correct.

The stars detected in C II at B-V=0.25 are HD25052 and HD90132. The former is a strong X-ray source, a Hyd., and a binary with a G dwarf. The latter is an apparently single AS dwarf. Simon and Landsman (Ref. 12) show that 53 Tan (B-V=0.26) also exhibits strong C II emission.

4. FLUX-COLOR DIAGRAMS

The C II flux (Fig. 2) increases with increasing T eff to B-V=0.3, but drops rapidly thereafter, although significant emission is visible as far as B-V=0.2. The logarithmic range in observed CII fluxes is over an order of magnitude for B-V≥0.4, but only a factor of 3 for 0.3≤B-V<0.4. The minimum in the range is actually an artifact of the sharply increasing minimum flux level. The scatter again increases into the late A dwarfs. It is not clear how this is to be interpreted, as the limits imply a very fast, almost instantaneous drop in the minimum flux level while the 3 detections are consistent with a much more gradual decline. In any event, the decline in transition region heating in the
A stars is much faster than predicted by models of acoustic wave heating of the lower atmosphere (Ref. 13). The computed acoustic fluxes are overplotted on the observed transition region fluxes in Fig. 4.

Figure 4: As Figure 2, but with the acoustic flux (Ref. 13) available overplotted. The two curves are for log g=4.0 and 4.5. The scaling is arbitrary. The shape of the computed curves matches the observed upper envelope of the transition region fluxes, but neither the lower limit (which is presumably acoustic in nature) nor the turnover in the late-A stars. Also overplotted is our preliminary estimate of the basal flux level.

5. FLUX-FLUX RELATIONS AND BASAL FLUXES

The power-law relations between flux densities in chromospheric transition region, and coronal emissions have been shown to hold for late-F through early-M type dwarfs and giants, for both single stars and members of multiple systems, provided an empirical lower limit, or basal, flux density is subtracted (Ref. 14). Basal fluxes are largest for the chromospheric emissions, and likely to be negligible for the coronal X-rays. The fluxes corrected for the basal fluxes (the excess fluxes) are identified with the (magnetically) active part of the stellar atmosphere. The basal fluxes may be due to non-magnetic acoustic heating.

Since the basal component in late-A and early-F type stars is very strong, the C II and C IV excess fluxes are very sensitive to errors in the observed fluxes and colors. Walter and Schrijver (Ref. 7) demonstrated that if an empirically determined basal flux is subtracted from the observed stellar flux then the early F stars follow the relation between the X-ray and C II excess flux densities defined by cooler stars (their Fig. 2), where the basal flux correction is generally negligible. We have used here a different basal flux extrapolation of Rutten's C II power-law (Ref. 8) from the G stars. Although a good description of the lower envelope of the F stars, this basal flux gives poorer flux-flux correlations than did the steeper power-law used in Ref. 7. These differences point out the importance of being able to define the true basal flux accurately, as it is such a large fraction of the total flux in these stars.

6. CONCLUSIONS

The chromospheres and transition regions of the early F dwarfs appear to be strongly affected by the basal heating, which is uncorrelated with the X-ray emission or stellar rotation rate. The color dependence of the basal flux level (Fig. 4) is much more pronounced than the calculated variation with color of the mechanical energy generated in the upper part of the convective zone. Schrijver (Ref. 15) showed that the basal flux for the Mg II h and k lines does exhibit the color dependence expected of the acoustic flux. If the Mg II h and k and C II lower bounds both measure purely acoustic heating, then the upper chromosphere and transition region respond non-linearly to the generated mechanical flux, and hence appear to be very sensitive to changes in the photospheric and lower-chromospheric structure.

Walter and Schrijver (Ref. 7) suggested that the dynamo efficiency is supressed at a given rotational velocity or rotational period for stars hotter than B-V<0.4, although the dynamo remains operational down to B-V=0.3. Because of the magnitude of the basal flux correction in the F stars, and the lack of knowledge of its true functional form, this result is questionable. Using the power-law basal flux drawn in Figure 4, we find no such decrease in dynamo efficiency from the mid- to early-F stars (Fig. 5).

Figure 5: The mean C II flux F', corrected for the basal flux, as a function of v sin i. Solid circles are stars with 0.25≤B-V≤0.40; open circles represent stars with 0.40≤B-V≤0.50. The implied rotation-activity relation is F' vs. sin i (Ref. 15), but an equally acceptable alternative has a steeper relation which saturates for v sin i=40km s⁻¹.

There is no dependence of the excess flux on distance above the main sequence, as shown in Figure 6, or on color (aside from the general correlation of v sin i with B-V.

The drop in the transition region and X-ray fluxes below B-V=0.3 (Refs. 1, 2, 6) suggests that with the disappearance of the convective envelope, both the basal and active heating mechanisms cease to function. Conversely, if a convective envelope is sufficiently thick to produce acoustic heating, then it seems also capable of supporting dynamo activity.
Figure 6: The scatter of $\Delta F_C$, $\mu$ with the Stromgren luminosity parameter $\delta c_1$. No correlation of the excess flux with luminosity (or stellar evolutionary state, age, and mass) is evident.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

LINE FORMATION OF COOL CARBON STAR CHROMOSPHERES

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ABSTRACT

Based on adopted photospheric plus chromospheric models, we generate synthetic fluxes of the C II (UV 1/2) and both lower and higher lines for the Mg II (UV 1) lines in both complete (CRD) and partial (PRD) redistribution and compare them to IUE spectra of the carbon star TX Psc. Non-LTE calculations with the program PANDORA are made for H, C, Na, Mg, and Ca. For CRD only will constrained atmospheric models, the best fit to the Mg II line profiles gives a flux in the C II lines (produced, surprisingly, at the same depth as the Mg II lines) 2.6 times too great and produces too much emission in the Mg II line wings. PRD in the Mg II h and k lines in an expanding chromosphere with an adjusted temperature structure produces the observed Mg II emission. The reduction in temperature produces C II fluxes that match the IUE low resolution spectra.

Keywords: Ultraviolet spectra, partial redistribution, red giant stars, carbon stars, chromospheres.

1. INTRODUCTION

The IUE spacecraft has initiated research in the chromospheric structure of the coolest stars in the sky: the N-type carbon stars. The low-resolution, long-wavelength IUE spectra of seven N-type carbon stars have been published (Ref. 1) and a single, weak high-resolution IUE spectrum of the Mg II h and k lines in the star TX Psc (NO; C6,2) has been obtained (Ref. 2). Based on these IUE observations, the chromospheric structure of TX Psc can be investigated in detail by semi-empirical modeling with the non-LTE PANDORA code (Ref. 3).

In semi-empirical modeling, an arbitrary chromospheric temperature-density stratification under the assumption of hydrostatic equilibrium is attached to a radiative equilibrium photosphere. An emergent spectrum is generated with the assumption of statistical equilibrium in the bound energy states and a self-consistent solution of the radiative transfer equation. The chromospheric temperature profile is then altered systematically until a reasonable match is made between the synthetic spectrum and observations. In the calculations presented here, H I, H+, H II, C I, C II, Na I, Mg I, Mg II, Ca I, and Ca II are assumed in statistical equilibrium while all other species are assumed in local thermodynamic equilibrium (LTE). The effect of partial-redistribution is investigated in the formation of the Mg II h and k lines and the resulting changes in the temperature distribution.

2. OBSERVATIONS

TX Psc is an ideal prototype in the investigation of N-type carbon star chromospheres since it has a wealth of observational data. Photometric and spectral observations of this star in the visual and infrared have been reviewed by Johnson, Luttermoser, and Faulkner (Ref. 4). For TX Psc and other N-type irregular (I.b) variables, Balmer lines are not seen either in absorption or emission (Ref. 5) although Hα lies among many strong CN lines and may not be obvious if present. However the lack of strong Balmer features is puzzling since TX Psc along with six other N-type irregular variables display emission lines from singly ionized metals in their low resolution IUE spectra (Ref. 1). Such emission lines are generally considered chromospheric indicators, and a temperature rise in the outer layers of this star might be expected to produce Balmer lines.

Two low resolution spectra, LWP 3168 and LWP 3170, (Ref. 6) were taken immediately before and after the 13.5-hour high resolution spectrum LWP 3169 (Ref. 2). The strongest emission lines on the low-resolution spectra, shortward of 2850 Å are Mg II (UV 1) near 2800 Å and C II (UV 0.01) near 2325 Å. Identifications of other emission features can be found in Ref. 1.

The C II lines near 2325 Å are the transitions between the 2p2 2p 2P0 and 2s 2p 4P states. These optically thin lines have been shown to be an electron density diagnostic in stellar atmospheres (Ref. 7). Although they are the second strongest emission feature in the low-resolution IUE spectra, they do not appear on the high-resolution IUE spectrum and we consequently cannot use them to deduce the electron density. However, we can use the integrated flux of these lines from the low-resolution spectra (2.6 x 10^-16 watt/m² from LWP 3168 and 3.2 x 10^-16 watt/m² from LWP 3470) as a check of the temperature-density stratification determined from the Mg II h and k line profiles.

The Mg II h and k lines (i.e., multiplet UV 1) are the resonance transitions of this ion (3s 2S - 3p 3P0) at 2795.5 Å and 2802.7 Å. The Mg II emission profiles are blue shifted with respect to the central self-absorption and are strongly affected by circumstellar absorption — especially on the short-wavelength side of the k line. We have suggested that the bulk of the circumstellar absorption is due to Mn I (UV 1), Fe I (UV 3), and Mg II self-absorption (Ref. 2).

Beside the visual and infrared spectral-photometry and IUE spectra, TX Psc has a measured angular diameter of 9.31 ± 0.75 milli-arcseconds by lunar occultation (Ref. 8). This allows absolute flux calibrations to be made with the synthetic flux which allows direct synthetic flux comparisons with the observations. The effective temperature has been determined to be 3080 K ± 150 K from this measured angular diameter and bolometric flux (Ref. 8) and the radial velocity is -25 ± 4 km/sec as measured from photoelectric lines (Ref. 9).

The chemical composition of TX Psc has also been determined (Ref. 10). For the adopted values of $T(\text{eff}) = 3080$ K and the photospheric microturbulent velocity ($v$) of 2.2 km/s: $^{12}$C/$^{13}$C = 43, $^{13}$C/$^{12}$C/O = 1.027, $^{12}$C/($^{13}$C+$^{12}$C)/O = +0.16, $^{12}$N/H = -0.27, $^{16}$O/H = -0.10, $^{12}$Ca/H = -0.3, and $^{16}$Fe/H = -0.4. Except for carbon, the metals are underabundant with respect to the Sun.

### 3. NON-LTE FLUX CALCULATIONS

We now solve the radiative transfer and statistical equilibrium equations with the PANDORA program (Ref. 3) in a horizontal homogeneous, plane-parallel atmosphere. We take the semi-empirical approach in modeling the chromosphere of this star. Using a radiative equilibrium model with $T(\text{eff}) = 3080$ K, $g = 0.01$ m/s², and C/O = 1.05 (Ref. 11) as a representative photospheric model of TX Psc, we attach an arbitrary temperature-density profile in hydrostatic equilibrium to the outer layers of the radiative equilibrium model to mimic a chromosphere. We then solve the radiative transfer and statistical equilibrium equations and produce an emergent spectrum. Since the angular diameter of TX Psc is known, an absolute flux comparison can be made between the synthetic and observed spectrum. The chromospheric temperature-density stratification is altered accordingly until the synthetic flux matches the observed flux.

We use the following initial iterative procedure for the flux calculations: (1) a 3-level H atom is converged for the given model with Lyman-α and Lyman-β assumed in detailed balance. (By convergence, we mean the level populations, source functions, and net radiative brackets remain constant with subsequent iterations.) Hydrostatic equilibrium then takes the total density as a function of height ($z = 0$ is set at unit continuum optical depth at 5000 Å). (2) We next converge the following atoms and ions: C I (7-levels), C II (7-levels), Ca I (7-levels), Ca II (6-levels), Na I (7-levels), Mg I (7-levels), and Mg II (6-levels). All other species are assumed in LTE. The microturbulent velocity is set to 5 km/s at all depths for all transitions.

#### 3.1 Complete Redistribution in a Static Atmosphere

This first stage of the non-LTE calculations make the assumptions of complete redistribution (CRD) in a static atmosphere for all radiative transitions. The continuous opacities used in these calculations include Hα and Hβ bound-free and free-free, H I, He I, He II, and He free-free, electron scattering, H I, H2, and He I Rayleigh scattering, and the bound-free opacities H II, He I, He II, C I', Na I, Mg I, Al I, Si I, Ca I, and Fe I.

We found it exceedingly difficult to produce Mg II h and k emission in the synthetic flux in higher oscillator strengths and the low density of our model. Because the inclusion of the Hα (4p 3p³) bound-free opacity in source function calculations, a "pure" absorption line would result no matter how steep a temperature gradient was included in the chromosphere. However, the inclusion of this C I bound-free opacity in the source function allowed the continuous opacity to exceed the line opacity to a greater height in the photosphere, which enables the monochromatic source function (S) to follow the Planck function ($\phi$) to a greater height. Instead of a steady decrease of the source function with height, a local maximum in the source function can form in the chromosphere, which in turn enables "emission-bumps" to form in these lines.

Figure 1 shows the final CRD flux calculation for Mg II h and k and compares it to the high-resolution IUE observation. The synthetic profiles are convolved with a Gaussian with the IUE-FWHM at 2800 Å of 0.17 Å and scaled to the angular diameter of TX Psc. The line wings have too much flux as compared to the observations however. Various chromospheric structures were tried with no success on decreasing the flux of these line wings. The only mechanisms that will reduce these wings is an increase of continuum pure absorption to higher layers in the photosphere (hence producing the same effect as the Ca I (4p 3p³) opacity) or partial redistribution (PRD) in the source function calculations (which thermalizes the line in higher layers).

![Figure 1](image-url)

The integrated flux of the C II (1V 0.01) multiplet for this model ($5.6 \times 10^{-16}$ watt/m²) however is ~2.6 times the observed flux of the two low resolution IUE spectra that bracket the high-resolution spectrum. These lines are formed at the same depth as the Mg II h and k emission peaks. Due to their lower oscillator strengths, C II (1V 0.01) is more closely coupled to the Planck function than Mg II h and k, as such, this CRD model cannot be the correct one for TX Psc.

#### 3.2 Partial Redistribution in a Static Atmosphere

The low densities in this model atmosphere allow line scattering processes to dominate pure absorption processes. As such, a proper treatment of the redistribution of scattered photons must be incorporated. We follow the partial redistribution (PRD) described by Ref. (3): c.f. Appendix A. PRD assumes photons in the line core will be completely redistributed (CRD) throughout the core as defined by a characteristic line-core half-width $\chi$ and photons in the line wings are assumed to scatter coherently.
The assumption of coherent scattering in the line wings in PRD allows the line source function to thermalize to the Planck function at higher depths in the photosphere compared to CRD. This means that the mean intensity \( I \) follows \( B \) to higher layers which produces a lower minimum in \( S \) in the outer photosphere. This in turn allows a steeper source function gradient in the lower chromosphere enabling the line wing flux to decrease.

Since the PRD line core photons cannot escape as easily in the wings as the CRD photons, the height of the Mg II emission profiles near line center is increased. This requires a decrease in the electron temperature in the layers where the Mg II emission profiles are formed. Figure 2 shows the resulting "best fit" of the synthetic spectrum in PRD as compared to the high-resolution IUE spectrum. The synthetic spectrum has been shifted by the radial velocity of TX Psc (+12 km/s). For these calculations, \( x \) is set to 6 Doppler widths. Except for the velocity shifts of the emission features, these lines now begin to reproduce the IUE spectrum fairly well. The lower temperature in these layers also produces a \( C \) II \( (\text{UV} 0.01) \) integrated multiplet flux of \( 2.8 \times 10^{-16} \text{ watt/m}^2 \). Figure 3 displays the temperature as a function of height for this "PRD" model and compares it to the "CRD" model.

3.3 Partial Redistribution in an Expanding Atmosphere

Mg II \( h \) is less affected than the \( k \) line by circumstellar absorption and as such displays the velocity blue-shift of the emission wings with more clarity. Figure 2 shows that the self-absorption portion of Mg II \( h \) is at rest with respect to the radial velocity of the star. Since this portion of the line comes from the upper chromosphere, these layers are expanding, if at all, at a very low velocity with respect to the photosphere. The emission portion of the line originates in the lower chromosphere where \( S \) reaches a local maximum. In this region, we introduce a velocity field with \( \langle v \rangle \text{max} \) occurring where \( dS/dh = 0 \) in the chromosphere. For the layers below this region, we follow the continuity equation to describe the velocity field at various heights in the atmosphere. For layers above this region, we reduce the velocity sharply to 2 km/s at the top of the chromosphere since the continuity equation produces unrealistic velocities in the outermost layers due to the low densities. Several values of \( \langle v \rangle \text{max} \) were tested to reproduce the \( h \) line. The chromospheric maximum expansion velocity was found to be approximately 40 km/s. Figure 4 displays the resulting flux for the Mg II doublet and Figure 5 displays the expansion velocity as a function of height.

![Figure 2. Comparison of our best "PRD" static atmosphere flux calculation to the high-resolution spectrum of Mg II k and h. Like Figure 1, the synthetic spectrum has been convolved with the instrument profile and shifted by 12 km/s.](image)

![Figure 3. Temperature as a function of height for the "CRD" model (dash) and the "PRD" model (solid).](image)

![Figure 4. Comparison of our best "PRD" expanding atmosphere flux calculation (convolved and shifted) to the IUE spectrum.](image)
4. CONCLUSION

We construct a semi-empirical chromospheric model of TX Psc based on the Mg II h and k line profiles, C II \((UV 0.01)\) integrated line flux, and overall appearance of the low resolution, long wavelength region of H E. The uniqueness of this model is fairly certain as a global-average of TX Psc's chromosphere due to the difficulty of matching the observational constraints. The outermost layers of this model are the most uncertain due to the lack of spectral indicators that arise from this region. The temperatures and densities in the outermost layers are constrained to force the optical depth of Mg II h and k to be small at the top of the atmosphere. The probable error in the middle and lower chromosphere \((-10^8 < z < -5 \times 10^6 \text{ km})\) is approximately \(\pm 50 \text{ K}\) since any temperature change greater than this has significant effect on the chromospheric spectral indicators.

Besides the uniqueness of this one-component chromosphere, we make the following observations from this study: (1) The chromospheric temperature rise must begin at a low enough density (in this model \(\rho(T_{\text{min}}) = 3 \times 10^{12} \text{ g/cm}^3\)) to (a) allow strong neutral metal lines (especially Mg I \(\lambda 2852 \text{ A}\)) to have a small enough opacity to be weakly affected by the chromospheric temperature rise (although it may be possible to hide such emission with circumstellar absorption), (b) prevent Balmer lines from becoming too strong, and (c) allow semi-forbidden lines like C II) and Al III to form. (2) The temperature gradient in the lower chromosphere must be high \((3600 \text{ K over three pressure scale heights — the geometric extent of the lower chromosphere})\) to produce the required emission in Mg II h and k and C II \((UV 0.01)\). (3) Ca I \((4p 4p')\) bound-free opacity must be included in the Mg II h and k calculations to produce emission features. (4) Partial redistribution effects in the resonance lines are very strong and must be used in the Mg II h and k calculations. Finally, (5) the lower chromosphere is expanding away from the photosphere near \(40 \text{ km/s}\) but the upper chromosphere is nearly static with respect to the photosphere.

5. REFERENCES

Nine chromospherically active single K giants have been identified from several surveys of chromospherically active stars. These stars have \( v \sin i \)'s ranging from 6-46 km s\(^{-1}\). Such large velocities are not explained by current scenarios of main sequence to giant star evolution. Fluxes of the ultraviolet emission lines of these stars are substantially less than those of FK Comae. Many of these giants have a moderate or strong lithium line strongly suggesting that these stars have just recently evolved from rapidly rotating A or early F stars as is suggested by their space motions. Thus, they are not spun down FK Com stars. The characteristics of these stars are such that they may be confused with pre-main-sequence stars. The primary difference may be that the post main sequence stars have strong Hα absorption lines while the pre-main sequence stars appear to have a weak Hα absorption line or possibly Hα in emission above the continuum.

Keywords: Giant Stars, Rapidly Rotating, Single, Chromospheric Activity, Lithium

1. INTRODUCTION

From spectroscopic surveys of active-chromosphere stars Fekel, Moffett, and Henry (Ref. 1) and Collier-Cameron, Lloyd Evans, and Balona (Ref. 2) have identified nine G8-K2 giants with moderate rotation (\( v \sin i = 6-46 \) km s\(^{-1}\)) but no apparent velocity variations. Such stars are unusual. Gray (Ref. 3) determined values of \( v \sin i \) for 23 G2-K2 giants and noted a sharp drop in \( v \sin i \) from about 25 km s\(^{-1}\) to less than 5 km s\(^{-1}\) at spectral type G3 III. He argued that this drop in \( v \sin i \) was the result of magnetic braking as the star evolved. Rutten and Puyler (Ref. 4) claim that the magnetic braking timescale is substantially longer than the post-main-sequence evolutionary timescale for such giant stars. Instead they claim that the drop in \( v \sin i \) is accounted for by changes in the moment of inertia and the stellar radius during the evolution from dwarf to giant. The rotational velocities of many of the active-chromosphere single giants are much too large for either theory.

The properties of these nine stars observed to date are given in Table 1. Columns 1-9 are HD number of the star, the \( V \) magnitude, \( B-V \) color, the mean velocity of the star and its r.m.s. uncertainty, \( v \sin i \), photometric period, \( P \sin i \), the qualitative strength of Hα absorption and the qualitative strength of the lithium line. The values of \( P \sin i \) were determined assuming the photometric period is the period of rotation. The depth of the Hα absorption feature is classified as weak if the line depth is less than 0.25, as moderate if the line depth is between 0.25 and 0.5, and as strong if the line depth is greater than 0.5. The lithium line is classified as weak if the line depth is less than 0.1, as moderate if the line depth is between 0.1 and 0.25, and as strong if it is greater than 0.25.

3. DISCUSSION

These stars may have evolved to their present evolutionary state in several ways. Bopp and Rucinski (Ref. 5) found several single rapidly rotating (\( v \sin i = 50-100 \) km s\(^{-1}\)) G and K giants which were photometrically variable and had variable Ca II H and K emission and variable Hα emission. The prototype of the group is FK Comae. Bopp and Rucinski suggested that such a star results from the coalescence of a U UMa binary as predicted by the evolutionary models of Webbink (Ref. 6). Bopp and Stencel (Ref. 7) obtained ultraviolet spectra of FK Com and HD 199178 with the International Ultraviolet Explorer (IUE) satellite. These spectra showed variable chromospheric and transition-region line emission. The flux in these emission lines is equal to or greater than that of the most active RS CVn binaries.

After coalescence the new single star would begin to lose angular momentum. Its active-chromosphere characteristics such as rotation and strong emission line flux would decrease with time. If the stars in Table 1 are spun down FK Com stars they would not necessarily be at odds with the scenario of Rutten and Puyler (Ref. 4), since they did not evolve as a single star to their present state.

A second possibility is that single rapidly rotating G-K giant stars have evolved from very rapidly rotating early-type, A or early F, stars. Such stars could have large main-sequence rotational velocities.
velocities and would evolve relatively rapidly to the K III stage. Bopp and Stencel (Ref. 7) rejected this possibility for the FK Com stars since if they evolved from main sequence stars without any loss of angular momentum, their main sequence rotational speeds would exceed the breakup velocity. If the stars of Table 1 have evolved from single A or early-F type stars, then their rotational velocities are inconsistent with the explanation of Gray (Ref. 3) and the simple models of Rudden and Polymer (Ref. 4).

There appear to be several major differences between FK Com and similar stars such as HD 199178 and the stars in Table 1. First, most of the \( v \sin i \)'s in Table 1 are substantially less than 100 km s\(^{-1}\). Second, except for HD 196811 all the stars have a moderate or strong H\(\alpha\) absorption line. Ultraviolet spectra with the IUE satellite have been obtained so far for seven of the stars listed in Table 1. In Table 2 their ultraviolet emission line fluxes are compared with those of FK Com. The observed fluxes of FK Com are substantially greater than those of the other single giants. Converting the observed fluxes to surface fluxes increases the flux differences relative to FK Com. The activity in the K giant stars of Table 1 as judged from their H\(\alpha\) line and ultraviolet fluxes is much less than that found in the FK Com stars.

From the line fluxes in Table 2 it is not possible to decide whether these stars are FK Com stars in the process of being spun down or are recently evolved early-type stars which have not been completely spun down.

Guinan, Bradstreet, and Robinson (Ref. 8) have concluded from an analysis of the space motions of \( ^{\text{W}} \) UMa stars that they are old disk population stars with a mean age of 5-10 billion years. Guinan and Robinson (Ref. 9) have shown that the space motions of FK Com itself indicate that it is a member of the old disk population. This is consistent with the suggestion that it is a coalesced \( ^{\text{W}} \) UMa star.

Collier-Cameron, Lloyd Evans, and Balona (Ref. 2) have compared the velocity dispersion of the single active subgiants and giants in their sample to those of mid-A, mid-F, and field subgiant stars. The single stars have a velocity dispersion midway between those of the mid-A and mid-F stars. This suggests that most of the stars in Table 1 have evolved from single main-sequence stars rather than coalesced \( ^{\text{W}} \) UMa systems.

If these stars have relatively recently become giants as evidenced by their still relatively rapid rotation, the giants would not have had a convective outer atmosphere for an appreciable time. Since it is believed that a star's surface lithium abundance is depleted when convective mixing causes dilution of the surface abundance, these giants could still have substantial lithium abundances. Lambert, Dominy, and Svertson (Ref. 10) found little or no lithium in inactive K giants.

Seven of the nine stars listed in Table 1 have been observed. The lithium feature was detected in all seven. The strongest lithium line was found in HR 454 = HD 9746 (Fig. 1). Its line depth of 0.8 reaches 0.2 or the intensity scale! Abundance determinations for the seven stars are being obtained with spectrum synthesis techniques. The detection of lithium in these stars is additional support for the theory that these stars have evolved from single early-type stars rather than coalesced from an old \( ^{\text{W}} \) UMa system.

The rapid rotation, ultraviolet and Ca II H and K emission, and strong lithium line seen in these post main-sequence stars are also characteristics of pre-main-sequence and very young main-sequence K stars such as HD 36705 (Ref. 11) and HD 82558 (Ref. 12), respectively. Thus, there is a serious possibility of confusing the evolutionary states, particularly for subgiants. The primary observa-

<table>
<thead>
<tr>
<th>( y_n )</th>
<th>( V )</th>
<th>( B-V )</th>
<th>Velocity</th>
<th>( v \sin i )</th>
<th>( P ) phot</th>
<th>( R \sin i )</th>
<th>( H\alpha ) absorption</th>
<th>Li</th>
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<td>9746</td>
<td>5.92</td>
<td>1.21</td>
<td>-42.4 ( \pm ) 0.4</td>
<td>8</td>
<td>7b</td>
<td>12</td>
<td>moderate</td>
<td>strong</td>
</tr>
<tr>
<td>17144</td>
<td>8.22</td>
<td>1.21</td>
<td>5.0 ( \pm ) 0.4</td>
<td>15</td>
<td>16.2</td>
<td>5</td>
<td>strong</td>
<td>moderate</td>
</tr>
<tr>
<td>27536</td>
<td>6.27</td>
<td>0.91</td>
<td>5.1 ( \pm ) 0.4</td>
<td>5b</td>
<td>310</td>
<td>37</td>
<td>strong</td>
<td>weak</td>
</tr>
<tr>
<td>31993</td>
<td>7.53</td>
<td>1.14</td>
<td>13.2 ( \pm ) 0.6</td>
<td>31</td>
<td>?</td>
<td>?</td>
<td>strong</td>
<td>strong</td>
</tr>
<tr>
<td>33788</td>
<td>7.0</td>
<td>22.0 ( \pm ) 0.7</td>
<td>29</td>
<td>9.8</td>
<td>6</td>
<td>strong</td>
<td>weak</td>
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<tr>
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<td>6.92</td>
<td>1.12</td>
<td>3.0 ( \pm ) 0.4</td>
<td>15</td>
<td>28.3</td>
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<td>weak</td>
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<tr>
<td>37434</td>
<td>6.09</td>
<td>1.17</td>
<td>16.0 ( \pm ) 0.5</td>
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<td>10.4</td>
<td>9</td>
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<td></td>
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<tr>
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<td>8.06</td>
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<td>6</td>
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<td></td>
</tr>
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<td>203251</td>
<td>7.99</td>
<td>1.22</td>
<td>18.0 ( \pm ) 0.6</td>
<td>40</td>
<td>?</td>
<td>?</td>
<td>strong</td>
<td>strong</td>
</tr>
</tbody>
</table>
Table 2

UV Emission Line Fluxes Observed at the Earth

\((10^{-12} \text{ ergs cm}^{-2} \text{s}^{-1})\)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength</th>
<th>HD 17144</th>
<th>HD 27536</th>
<th>HD 31993</th>
<th>HD 33798</th>
<th>HD 34198</th>
<th>HD 37454</th>
<th>HD 20351</th>
<th>FK Com</th>
</tr>
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<tr>
<td>N V</td>
<td>1240</td>
<td>-</td>
<td>0.5</td>
<td>0.8</td>
<td>0.6</td>
<td>1.7</td>
<td>1.2</td>
<td>0.3</td>
<td>3.2</td>
</tr>
<tr>
<td>O I</td>
<td>1305</td>
<td>0.9</td>
<td>0.8</td>
<td>3.2</td>
<td>1.6</td>
<td>0.2</td>
<td>3.2</td>
<td>1.3</td>
<td>14.5</td>
</tr>
<tr>
<td>C II</td>
<td>1335</td>
<td>0.3</td>
<td>0.8</td>
<td>0.8</td>
<td>1.2</td>
<td>2.0</td>
<td>0.9</td>
<td>0.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Si IV</td>
<td>1400</td>
<td>-</td>
<td>1.5</td>
<td>0.8</td>
<td>0.6</td>
<td>2.7</td>
<td>1.8</td>
<td>-</td>
<td>6.9</td>
</tr>
<tr>
<td>C IV</td>
<td>1549</td>
<td>0.4</td>
<td>0.7</td>
<td>1.4</td>
<td>2.2</td>
<td>4.7</td>
<td>2.6</td>
<td>1.0</td>
<td>13.5</td>
</tr>
<tr>
<td>Ca II</td>
<td>1640</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>0.8</td>
<td>0.9</td>
<td>0.3</td>
<td>0.2</td>
<td>4.0</td>
</tr>
<tr>
<td>C I</td>
<td>1657</td>
<td>0.6</td>
<td>-</td>
<td>0.5</td>
<td>1.2</td>
<td>2.3</td>
<td>0.9</td>
<td>1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Si II</td>
<td>1815</td>
<td>-</td>
<td>2.0</td>
<td>1.0</td>
<td>1.4</td>
<td>2.9</td>
<td>2.3</td>
<td>0.9</td>
<td>5.8</td>
</tr>
<tr>
<td>Mg II</td>
<td>2800</td>
<td>-</td>
<td>87.0</td>
<td>-</td>
<td>-</td>
<td>110.0</td>
<td>-</td>
<td>-</td>
<td>208.0</td>
</tr>
</tbody>
</table>

Figure 1. A spectrum of the lithium region showing the very strong lithium line (6708 Å) of HR 454 relative to its calcium line (6717 Å).
tional difference appears to be that the premain
sequence and young main sequence stars have an Hα
line which is a strong absorption feature. Second-
ly, the period of photometric variability
which is usually identified as the rotation period
is substantially greater for the post-main-se-
quence giants due to their larger radii. However,
this may not be the case for subgiants.

This work has been partially supported by several
NASA grants with F. C. Fekel as principal investi-
gator.

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MG II FLUX AND PROFILE VARIABILITY OF HYBRID-CHROMOSPHERE STARS

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ABSTRACT

Results from an investigation of the variability seen in the Mg II emission line fluxes and wind absorption components of a number of hybrid-chromosphere stars are presented. Real Mg II flux variability is shown with most of the variation being long-term. This variability appears to be due to global changes in the Mg II surface activity. Major changes in the wind absorption component were not seen.

Keywords: Stellar chromospheres; Stellar winds; Hybrid-chromosphere stars

1. INTRODUCTION

Hybrid-chromosphere stars are luminous cool stars that possess an unusual set of atmospheric characteristics. Their ultraviolet spectra show both transition region (TR) plasma (T\textsubscript{e} = 10\textsuperscript{5} K), as evidenced by C IV, Si IV and N V emission lines and a substantial stellar wind, as evidenced by high velocity (100-200 km/s) blue-shifted absorption in the Mg II h and k lines (Refs. 7, 11). Hybrid stars have been found in two particular regions of the HR diagram, namely among early G-type supergiants and early K-type bright giants. Brown (Ref. 3) showed that TR emission is common among early K bright giants but that only about half these stars have obvious high velocity wind absorption, however it is possible that at least a few of the other stars have winds with even higher velocities. Brown, Reimers and Linsky (Ref. 4) showed that the TR plasma is at rest velocity and not within the high velocity wind. This implies that either the TR and wind are physically separate (Ref. 10) or that the hotter plasma lies at the turbulent base of the wind (Refs. 2, 8).

Drake, Brown and Linsky (Ref. 6) studied the Mg II absorption components of hybrid stars. Two absorption features are seen; Drake et al. (Ref. 6) concluded that the high velocity components are formed in the stellar wind while the narrow low velocity components are primarily due to the interstellar (IS) medium. O'Brien and Lambert (Ref. 11) showed that the He I 10830 A lines of hybrid stars behave unusually with strong variations from emission to absorption and outflow to inflow; unfortunately the formation of this line is poorly understood. Brosius, Mullan and Stencel (Ref. 2) studied the variability of the integrated Mg II line fluxes of hybrid stars. They found changes in the line flux that they interpreted in terms of rotational modulation. Oznovich and Gibson (Ref. 12) cast some doubt on the findings of Brosius et al. (Ref. 12) but did find emission line flux variability from SWP spectra of the hybrid stars α Aqr, γ Aql and δ Oph.

2. OBSERVATIONAL DATA

During the 8th IUE year (program LGHJL) we monitored the Mg II emission lines of 7 hybrid stars at roughly monthly intervals to test the claims of Brosius et al. (Ref. 2) and to produce an enhanced dataset with which to investigate the atmospheric variability of hybrid stars. In addition to our own data, we have analyzed all the available long-wavelength images for these stars that have appropriate exposure times. Images with short (usually 5-30 minutes) exposure times were used to measure the Mg II emission line fluxes, while deeper exposures were used to search for variability in the wind absorption components. The fluxes of both the h and k lines were measured and for each line the total flux and the flux redward of the IS absorption were measured to see if variability was due to changes in total line flux or merely changes in the wind absorption. Table 1 shows the number of spectra available for each type of measurement, while Table 2 presents the standard deviations, expressed as percentages, found for each of the measured quantities. This analysis was all performed at the Colorado IUE Regional Data Analysis Facility using the ICUR.
The temporal behavior of the Mg II h emission line flux measured redward of the IS absorption for four K bright giant hybrid-chromosphere stars. Note that many of the values obtained close in time (e.g. the latter parts of the coverage of α Tra and γ Aql) agree very well. Ranges of ±10% are shown for each star. When contrasted with the measurement error of 5% this implies real variability for all four stars. Note that for at least 1700 days the flux for ζ Aur was essentially constant. The variability of γ Aql may be similar to behavior expected from stellar activity cycles.
Figure 2. The ratio of the total Mg II emission line flux to the flux redward of the IS absorption for two hybrid-chromosphere stars. Note that the ratio of the fluxes stays almost constant, while the total line flux varies. This implies that true global changes in stellar activity are occurring rather than merely line profile changes.

Table 2. Percentage 1σ variation

<table>
<thead>
<tr>
<th>Fluxes &amp; Wind</th>
<th>k</th>
<th>k' red</th>
<th>h</th>
<th>h' red</th>
</tr>
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<tr>
<td>α Aqr</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>δ Aqr</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>λ Aqr</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>η Aqr</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Ω Aqr</td>
<td>16</td>
<td>11</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>ε Her</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

Program developed by Dr. Fred Walter. The measured emission line fluxes were corrected for long term changes in the sensitivity of the IUE cameras (Ref. 5) and for temperature effects (Ref. 9).

3. ACCURACY OF OUR TECHNIQUES

For the Mg II line fluxes we found that relative flux measurements are accurate to better than 5% and that fluxes from similar optimum spectra taken in the same shift agree to better than 3%. Considerable care must be taken in the study of Mg II flux variability and we find that it is best to: a) only compare the same line in the same order, rather than mixing measurements from both orders (for much of the previous data this introduces a 10% spread due to the incorrect ripple correction); b) use a fixed wavelength interval for a given line of each star (this interval can be shifted somewhat to allow for image displacement on the camera), as this is much easier to apply systematically than trying to estimate where each line ends on an individual spectrum; c) not use data acquired when the radiation background is above 2.7 volts as these always give systematically higher emission line fluxes, even when no obvious noise spots are evident, and; d) not use emission lines that are saturated or affected by obvious noise spots.

The cleanest results are found using either the total flux or only the flux redward of the interstellar line for the G supergiant hybrids but better results are found when using the flux redward of the IS line for the K bright giant hybrids. This occurs because the flux shortward of the IS line for the K stars is very weak and extending the wavelength coverage only increases the noise in the measurement. Of course if a deeper exposure is combined to define the weaker blue part of the line, then an accurate total flux can be derived. The IS absorption line velocities derived by Drake et al. (Ref. 6) and Brown (Ref. 3) were used to fix the velocity zero-point for the wind absorption measurements. This method provides relative velocity measurements that should be accurate to 1 km/s (1 standard deviation). The position of the high velocity edge of the wind absorptions were measured. In some cases this feature was not as easily seen as in most of the spectra and this may have introduced some error.
4. RESULTS

1. Real Mg II flux variability is present with even the more constant stars showing 3σ variations in excess of the spread expected due to measurement errors. The temporal behavior for some of the stars is shown in Fig. 1. In general the spread in flux is between 20 and 30% of the mean, with most of the variation being long-term.

2. In our larger sample there is no evidence to suggest the presence of rotational modulation of the emission line flux as suggested by Brosius et al. (Ref. 2).

3. The flux variability appears to be due to global changes in the Mg II surface activity rather than merely due to line profile variations, i.e. in particular the variability is not due to large changes in the flux absorbed by the stellar wind. This is illustrated in Fig. 2.

4. There is in fact very little evidence for major changes in the wind absorption components based on this sample. Previous deep exposures have shown large changes in the wind absorption of LTA (Refs. 4, 6, 8) but such changes are not discernible with the relatively weakly exposed spectra in our present study.

ACKNOWLEDGMENTS

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The Discovery of a Co-rotating Magnetosphere in a Helium Weak Star: HD 5737 = α Scl
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Abstract

Previous work on the sn stars has demonstrated the existence of magnetically controlled mass outflows in several stars. Here we report the discovery, using combined IUE spectroscopy and Zeeman polarimetric magnetic field measurements, of the first bona fide example of a magnetosphere in a helium weak star. HD 5737 = α Scl is one of the extreme He weak stars in its He deficiency, but is otherwise quite similar to the other sn stars HD 21699 and HD 79158. We report a unique period for the magnetic and C IV and Si IV variations of 21.65 days, about a factor of 10 longer than the other variable sn stars. The effective (longitudinal) field nulls correspond extremely well to C IV line strength maxima. The magnetic field and equatorial magnetosphere are highly oblique (about 70°) and the line variations appear to be stable.

1. Introduction

HD 5737 = α Scl is classified as a B8 III star according to the latest edition of the Bright Star Catalog, with the footnote that it is helium weak. The star has been recognized for some time as helium deficient (ref 1) and as one of the slowest rotators among this class of Bp stars. Its magnetic field has been observed by Borra et al. (ref 2) and Shore et al. (ref 3).

In a previous study of the sn stars (ref 3), we reported the discovery for HD 5737 of phase dependent C IV and Si IV line profiles, but at the time were unable to provide a proper period with which to phase the magnetic field and UV spectra together. HD 5737 has the additional property of showing only a tiny range of photometric variations, if it is in fact even variable. Kurtz and Marang (ref 4) have been unable to find a unique period for the star. Data reduction used the method previously employed for the sn stars. We formed synthetic photometry using:

\[ a(CIV) = \frac{1}{2}(m_{1462} + m_{1640}) - m_{1548} \] (1)

where all filters are rectangular profiles with 2 Å widths. Line strength is indicated by increasing \( a(CIV) \). All spectra were smoothed with a box-car filter to 3 pts to improve S/N as in our previous studies. For Si IV, we have used:

\[ a(SiIV) = \frac{1}{2}(m_{1307} + m_{1307.5}) - m_{1304} \] (2)

with all filters being 2 Å wide.

Magnetic measurements were made during 1987 Oct and 1988 Jan using the UWO Zeeman polarimeter on from even densely sampled magnetic data. The fact that the star is almost a magnitude brighter than the other sn stars which display C IV variations is offset by the southern declination of the star, and the small field.

HD 5737 is similar in temperature and luminosity to HD 21699, and somewhat hotter than HD 79158. To date, these are the only three sn stars which appear to show the phenomenology of UV spectrum variations that are normal among the helium strong stars (ref 6). HD 161480, another C II anomalous member of the class, has been observed twice during this program, and displays only normal Fe II/III absorption in both spectra (SWP 32022, and 32053). We have also observed HD 79158 in 1987 Oct and 1988 Feb and are currently analysing this data. In this report, we focus on HD 5737 only.

2. IUE and Magnetic Observations

Most of the observations we report here are new. Previous spectra will be found in (ref 3). All IUE spectra were obtained using the SWP camera in high dispersion, with the large aperture; all spectra were exposed for 2 min. The sequencing of exposures was optimized to search for periods between 10 and 30 days, the previously determined most probable period range. Magnetic observations by Borra et al. had suggested a period of about 16 days, but with considerable uncertainty. We used IUE in 14 halfshift allocations in to sessions spread out over a period of about 20 days. Data reduction used the method previously employed for the sn stars. We formed synthetic photometry using:

\[ a(CIV) = \frac{1}{2}(m_{1462} + m_{1640}) - m_{1548} \] (1)

where all filters are rectangular profiles with 2 Å widths. Line strength is indicated by increasing \( a(CIV) \). All spectra were smoothed with a box-car filter to 3 pts to improve S/N as in our previous studies. For Si IV, we have used:

\[ a(SiIV) = \frac{1}{2}(m_{1307} + m_{1307.5}) - m_{1304} \] (2)

with all filters being 2 Å wide.

Magnetic measurements were made during 1987 Oct and 1988 Jan using the UWO Zeeman polarimeter on

the SS in at Mauna Kea Observatory. Procedures for data reduction were the same as those in (ref 3).

We have also used synthetic photometry for the Si IV line, in order to check the degree of variability of the profile. Differenced spectra show, as in the earlier results, that the Fe II and Fe III spectra, responsible for most of the blending at C IV and Si IV, are not variable to within the accuracy of the SWP spectra.

3. Spectroscopic Results

Figure 1 shows the run of spectra during 1987 October, with figure 2 displaying the unphased a(C IV) data. The data are given in table 1. Differenced spectra for the orders containing the C IV doublet show that only C IV is variable. For C IV, a(C IV) = 0.295 ± 0.253. In contrast, a(Si IV) = 0.233 ± 0.076 for the same set of spectra. Consistent with the results reported in (ref 3), Si IV is far less variable than C IV.

We have used two different methods to determine the period, one due to Lister and Kinman (ref 7) and the other a stochastic fourier analysis method due to Searle (ref 8). A unique period emerges from the Lister-Kinman algorithm of 21.65 days, which also found from the periodogram analysis. The phased UV spectrum data is shown in figure 3. This now includes all available spectra, including archival data. Note that the variation is double-wave, unlike HD 21699 (ref 3, 9). The scatter is quite small. The synthetic photometry is considerably more accurate than equivalent width measurements, although well correlated, and immune to the errors of judgement that plague the latter. For comparison, in figure 4, we show Kurtz's U photometry phased on the 21.65 day period. There is some hint of variability, but the scatter is large enough (in spite of the intrinsic accuracy of the photometry) to obscure any periodic variation.

4. Magnetic Data

We have phased all of our magnetic measurements together with those of Borra et al. to produce a single magnetic curve. This is shown in figure 5. In order to assist later discussion, we have chosen an arbitrary initial epoch, JD 2443500, which is comfortably in advance of any available observations of HD 5737.

The errors associated with the magnetic measurements make it difficult, presently, to say definitively that the field varies sinusoidally. It reverses symmetrically with little offset; there is no evidence for a substantially displaced dipole, unlike many of the other helium weak stars. This argues that the field is dipolar, without substantial contributions from higher multipoles.

5. The Magnetosphere of HD 5737: A Preliminary Evaluation

The comparison of the magnetic and UV variations demonstrate that the C IV profile changes are due to the rotation of a magnetosphere across the line of sight. Magnetic nulls coincide with strongest C IV absorption, and the longitudinal field extreme coincide with C IV minima. Although there are some slightly negative a(C IV) measurements, these are consistent with nulls. Weakest C IV corresponds to the strongest positive projected magnetic field.

In light of these results, we can place some limits on the properties of HD 5737 and its magnetosphere. The rotational velocity of this star is poorly determined, but appears to be no larger than 15 km s\(^{-1}\) (ref 3). With a period of 21.65 days, and a radius of between 3 and 5 \(R_\odot\), we can use the formalism of ref (10) to determine the probable obliquity of the magnetic field. The phase separation of the a(C IV) maxima being \(\Delta \Phi\), the obliquity \(\beta\) is related to \(\Delta \Phi\) by:

\[
\cos\left(\frac{\Delta \Phi}{2}\right) = \cot\cot\beta
\]

For \(60^\circ < \beta < 90^\circ\), we obtain \(\beta \approx 70^\circ\) from both the magnetic and C IV profiles.

The magnetosphere appears to be nearly axisymmetric, and the variations of the line width suggest that it is co-rotating with the star to about 10 \(R_\star\). This value is consistent with the Alfvén radius expected for a co-rotating magnetosphere for a field strength of about 1 kG (ref 14). Comparison of the a(C IV) variations with models for banded oblique rotators calculated by Shore (ref 11) suggest that the band is consistent with a \(P(\theta_n)\) distribution, where \(\theta_n\) is the magnetic colatitude and \(P_3\) is the Legendre polynomial; in other words, the C IV variations are those expected from a simple optically thick band at the magnetic equator. There is no evidence for instability over nearly a decade, since the archival spectra phase very well with the most recently obtained observations.

At this juncture, we can only conjecture why HD 5737 shows a magnetosphere while HD 21699 shows a polar mass outflow. Many of the characteristics of the line profiles are similar, so there is no hint there as to why this should be the case. Instead, it is possible that the slow rotation plays the deciding role. Barker et al. (ref 6) argued that the slow rotators among the helium strong stars show substantially different line profiles at C IV than do the short period systems, and this may have to do with the opening angle of the polar cone. Most of the matter may be trapped in co-rotation rather than freely flowing from the star. HD 5737 shows no evidence for an IR excess, and the IRAS data at 12\(\mu\) are consistent with an effective temperature of 15000 K (it is the only Hе weak star in the IRAS point source catalog, due probably to its distance and relatively unconfused field). Because there is no substantial outflow indicated, we do not know if the heating could be the same as that observed in the polar flow of HD 21699. Rather, the C IV may simply be due to a normal NLTE effect of high ionization in a low density, trapped plasma. The star does not show any evidence for radio emission, as seen in the helium strong star HD 37479, perhaps because of the weak field. It is also possible that the field in this star is too weak to prevent the outflow from occurring at the magnetic equator, but that it is strong enough to trap and funnel matter once the flow has reached some distance from the star. The plasma appears to be trapped in a filled region, contiguous with the stellar surface (there is no evidence for a velocity gap in the profile, although it is very optically thick near line center...
which could obscure such an effect).

6. Summary

To summarize, HD 5737 has been discovered to display evidence for magnetospheric plasma, trapped at the magnetic equator, co-rotating with the stellar photosphere with a long period. It is the first helium weak star to show such behavior, which has been well established for the He strong stars. The behavior of this star is similar to HD 184927, which may also be a long period system and is one of the coolest of the helium strong stars.

We wish to thank Dr. T. Simon for trading several exposures during the 1987 October run without which we would not have been able to obtain such effective phase coverage. Dr. C. Schraeder is thanked for his heroic efforts in scheduling our request of an obnoxious number of half-shifts. We also thank Drs. P. Barker, T. Bastien, T. Bolton, J. Eilek, R. Hjellming, and T. LaRosa for interesting discussions.

Table 1. HD 5737: 1987 Oct. IUE C IV Data

<table>
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<th>SWP</th>
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References

Fig. 4. U photometry (Kurtz) on a(C IV) period.

Fig. 5. \( \omega_{\text{eff}} \) variations in a(C IV) period.
OBSERVATIONS OF ULTRAVIOLET VARIABILITY IN RV TAURI STARS

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Center for Astrophysics
and Space Astronomy
University of Colorado
Boulder, Colorado

ABSTRACT

During the tenth IUE observing epoch we initiated a program to monitor the ultraviolet variability in several RV Tauri stars. In particular, the Mg II region was investigated as a potential probe of atmospheric shocks, which are believed to be associated with the pulsational variability of this class of objects. We present the observations, a description of the spectra and our preliminary findings for two objects - V Vul and AC Her. In particular, the Mg II emission does vary significantly during the cycle; major changes in the emission line strength occur on a time scale much less than 0.2 in phase; and as the UV (and optical) continuum flux increases, the Mg II lines decrease and increased emission may be seen at 2823Å, 2844Å, and 2900Å.

Keywords: stars: variable - stars: RV Tauri - stars: atmospheres - shock waves - lines: emission

I INTRODUCTION

Among the variety of pulsationally unstable stars, RV Tauri stars stand out as a distinct and unique class of variables. This class of stars is characterized by alternating deep and shallow minima and tend to show spectral variations indicative of metal poor supergiants (II-lb, la) of type F, G, and K. Their periods, taken between successive deep or shallow minima, are typically in the range 30-150 days with the majority being around 50-100 days. From a spectroscopic standpoint, RV Tau stars can fall into three basic groups as first outlined by Preston et al. (1963). Type A consists of stars exhibiting features characteristic of G-K stars. Type B consists of stars exhibiting peculiar F type spectra as indicated by the continuum shape and the strength of the hydrogen and Ca II lines. Finally, type C objects tend to share the same characteristics as type B with the difference being that CN and CH absorption is weak or completely absent.

Furthermore, RV Tau variables often exhibit behavior indicative of stars undergoing mass loss. Many frequently show emission in the Balmer lines on the rise from primary and secondary minimum, while through other phases the higher Balmer lines appear partially filled in while Hα can remain in emission. A few stars (e.g. AC Her) have been studied optically at high spectral resolution and tend to display line doubling and weak metallic-line emission near primary minimum implying moving atmospheric layers and shock waves similar to Mira variables. For a recent review on atmospheric shocks see Willson and Bowen (1995). Finally, nearly all of the observed RV Tau stars show moderate to strong IR emission excesses indicating the presence of large amounts of circumstellar material. This, along with the presence of molecular absorption at phases where it is not expected to occur in the atmosphere of the star (the absorption probably arises in circumstellar gas shell(s) separate from the dust) as well as large variable polarization, indicate that mass loss is fundamental to RV Tau behavior and may provide a link to their evolutionary state.

II OBSERVATIONS

During our tenth year IUE program we monitored in low dispersion the Mg II variability of several RV Tauri stars, concentrating on the following four objects: AC Her, V Vul, EP Lyr and UU Her. In addition, several high dispersion observations were obtained of U Mon. Unfortunately, varying degrees of phase coverage were obtained for each, and no object has complete phase coverage over an entire cycle. Detailed spectrophotometric phase coverage (intervals of Δφ ≈ 0.1) during the course of a variable star's cycle is extremely useful since it provides essentially a continuous "history" of a star's atmospheric variations. However, gaps in the phase coverage and an insufficient sampling rate can make the "history" difficult to interpret. For this reason, we will concentrate herein on the two stars for which we have the best phase coverage - V Vul, a Preston type 'A' star, and AC Her, which is Preston type 'B'. A log of the IUE observations and summary of the detected Mg II strengths, either emission or absorption, appears in Tables I and II.

The low dispersion spectra were extracted from the spatially resolved line-by-line file provided by IUESIPS and then merged. The net spectra (gross - background) were then converted to a flux scale using the absolute calibration...
of Cassatella and Harris (1983). Though there are possible systematic errors in the absolute fluxes, the relative flux measurements are not similarly affected since all spectra were processed with the same calibration. A weak to moderate ultraviolet continuum was detected at and longward of 2900 Å for most of the low-dispersion observations. The significant variability in the UV continuum may contribute to the changes seen at Mg II. We estimate that the uncertainty in the integrated flux measurements for V Vul does not exceed ±10%.

### Table I

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<td>7075.03</td>
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- assumes max. light (phase 0.0) on JD 2447098

### Table II

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- assumes max. light (phase 0.0) on JD 2447114

II.1 Description of the V Vul Spectra

As evident from figure 1, the spectra of V Vul show a distinct Mg II emission at almost all phases. Starting with our first observation at optical phase 0.55 (± minimum light), the Mg II line strength is at a maximum and the UV continuum is very weak. With increasing phase from 0.55 through maximum light (at phase 0.0) to phase 0.22, the Mg II flux shows a smooth decline. In contrast, the UV continuum longward of 2800 Å shows a marked increase during the part of the cycle. There is also a hint of emission at 2831 Å, 2844 Å and 2900 Å (see figure 1, phase 0.07 - 0.26). These are probably Fe II lines, particularly the two shorter wavelength lines which are known Mg II/Fe II fluorescence lines (Carpenter et al. 1988). The Mg II emission appears to reach a minimum near phase 0.26 while the UV continuum seems unaffected from phase 0.07 to 0.47. By phase 0.55, the emission in Mg II is approaching the maximum strength observed in the previous cycle at phase 0.05, while the continuum has faded drastically.

III DISCUSSION

The use of IUE low dispersion spectra for the purpose of studying atmospheric shocks and mass loss has shown promise for the Mira variables (Brugel, Wilson, and Cardinas 1986, Brugel et al. 1987). This is particularly true when these data are combined with theoretical models such as those by Bowen (1988). Similarly, initial though phase limited observations had been attempted for a few RV Tauri stars (Dawson and DuPuy, 1986). In an approach complimentary to the Mira investigations, we have endeavored to extend the technique to the hotter and shorter period RV Tauri stars. As very preliminary results we note three aspects apparent in the observations presented here: (1) the Mg II emission does vary significantly during the pulsation cycle for some RV Tauri stars; this emission variability does maintain phase coherence with the optical pulsating; and it is undoubtedly associated with the propagation of an atmospheric shock; (2) major changes in the Mg II emission line strength occur on a time scale much less than 0.2 in phase, which was our sampling frequency (e.g. the Mg II flux in V Vul decreased from 2.40 x 10^-13 erg cm^-2 s^-1 to approximately zero in less than 22 days); and (3) high dispersion observations are required for AC Her in order to disentangle the Mg II emission from atmospheric absorption.

In addition, the low dispersion spectra for V Vul hint at asymmetric structure in the Mg II emission, which in high dispersion may yield information on the atmospheric velocity distribution in the post shock region.

II.2 Description of the AC Her Spectra

AC Her presents a similar yet distinctly different form of UV continuum and Mg II variability (see Figure 2). In this case, the Mg II line is generally seen in absorption, though at some phases the absorption is apparently partially filled in by emission. In low dispersion the anticipated Mg II emission cannot be disentangled from the absorption and high dispersion data are obviously required. Starting at phase 0.34 the Mg II absorption feature is rather shallow and the continuum is quite weak. As one progresses in phase to 0.48 through 0.67, the Mg II absorption deepens, the continuum strengthens and there appears some slight evidence for emission at 2900 Å. Only two tenths of a phase later, at phase 0.65, the absorption is significantly reduced and so is the continuum. Subsequently, there is little detected change through to maximum light, which was observed at phase 0.04.

RV Tauri stars are known for showing extreme cycle to cycle variations, even AC Her which is one of the most regular of the class show distinct differences from one cycle to the next. As an illustration, data taken in 1984 by Baird and Cardelli (1985) show significant Mg II emission at their phase 0.61, while our observations at phase 0.67 show close to a maximum absorption.

The use of IUE low dispersion spectra for the purpose of studying atmospheric shocks and mass loss has shown promise for the Mira variables (Brugel, Wilson, and Cardinas 1986, Brugel et al. 1987). This is particularly true when these data are combined with theoretical models such as those by Bowen (1988). Similarly, initial though phase limited observations had been attempted for a few RV Tauri stars (Dawson and DuPuy, 1986). In an approach complimentary to the Mira investigations, we have endeavored to extend the technique to the hotter and shorter period RV Tauri stars. As very preliminary results we note three aspects apparent in the observations presented here: (1) the Mg II emission does vary significantly during the pulsation cycle for some RV Tauri stars; this emission variability does maintain phase coherence with the optical pulsation; and it is undoubtedly associated with the propagation of an atmospheric shock; (2) major changes in the Mg II emission line strength occur on a time scale much less than 0.2 in phase, which was our sampling frequency (e.g. the Mg II flux in V Vul decreased from 2.40 x 10^-13 erg cm^-2 s^-1 to approximately zero in less than 22 days); and (3) high dispersion observations are required for AC Her in order to disentangle the Mg II emission from atmospheric absorption.

In addition, the low dispersion spectra for V Vul hint at asymmetric structure in the Mg II emission, which in high dispersion may yield information on the atmospheric velocity distribution in the post shock region.
Figure 1: A series of nine low dispersion LWP spectra of V Vul are presented. An offset in flux has been added to each successive spectrum and the corresponding zero flux levels are indicated by the dashed lines. Note the smooth decline in the integrated Mg II from phase 0.55 through 0.26, and the contrasting increase in the UV continuum.

Figure 2: A series of six low dispersion LWP spectra of AC Her are presented. An offset in flux has been added to each successive spectrum and the corresponding zero flux levels are indicated by the dashed lines. Note the strong Mg II absorption feature at phases 0.48 and 0.67, and that this feature is partially filled in by emission at other phases.
IV ACKNOWLEDGEMENTS

These data were reduced and processed at the University of Colorado's IUE-RDAF, which is supported by NASA contract number NAS5-28731. The research presented was supported by NASA contract NAG5-330 to the University of Colorado.

REFERENCES


Stellar Atmospheres & Variable Stars
ABSTRACT

Fluorescence processes active in the outer atmospheres of non-coronal cool stars and the UV lines they produce are summarized. Eight new pumping processes and 21 new fluorescent line products are discussed. The new processes, which produce 12 lines, involve energy levels not previously known to be radiatively populated. Four of these are examples of self-fluorescence, whereby one or more lines of Fe II photo-excite through coincident lines the upper levels of other Fe II lines seen in emission, while two others explain the selective excitation of solitary Ni II and Si I lines. Nine of the line products are newly recognized decays from levels in Fe I and Fe II already known to be radiatively populated.

Keywords: Fluorescence, Cool Stars, Chromospheres, Line Identifications, Fe II

1. INTRODUCTION

The fluorescence processes of importance to the UV spectrum of a single, non-coronal cool star (giants > K2, supergiants > G8) generally involve the radiative excitation of an atomic energy level by photons emitted from other ions or from other levels of the same ion, since there is no strong UV continuum source in these objects. The electrons then radiatively decay from the excited level, producing line radiation during one or more subsequent downward transition(s). There is only one clear case identified so far of fluorescence involving molecules in the UV spectra of these stars, the Ayres et al. O I - CO process (Ref. 1).

The outer atmosphere of a non-coronal cool star is an ideal locale for the operation of such line fluorescence processes. The low densities typical of late-type stellar chromospheres (log $N_e$ 9.0) imply a low rate of collisional de-excitation and allow the radiative decay of levels populated by selective radiative pumping. In addition, there are many strong sources of line radiation and many possible upward transitions from highly populated low-lying levels of abundant elements, especially in Fe II. There can thus be many chance coincidences between potential pumps and possible upward transitions.

In this paper we summarize all of the fluorescent processes known to be operating in the outer atmosphere of single, non-coronal stars and provide more details on the new processes and UV line identifications reported by Carpenter et al. (Ref. 2) for the M-giant Gamma Crucis. A companion paper by Johansson and Carpenter (this volume, Ref. 3) further discusses the two processes which involve new energy levels recently found in laboratory analysis of Cr II and Fe II.

2. FLUORESCENCE PROCESSES NOT PRODUCING Fe II

A number of fluorescence processes which do not produce Fe II lines have been known for some time. These include the Lyman Beta - O I (UV 2), the O I (UV 2) - S I (UV 9), the O I (UV 2) - O II, the Fe II (UV 3/34)/Si II - Co II (UV Si, and Mg II (UV 1) - Fe I (UV 44) fluorescence mechanisms. Further details on these processes and lines, as well as the new ones discussed below, are given in Table 1, along with appropriate references.

Carpenter et al. (Ref. 2) identify three new processes and fluorescent lines, as well as a line (Fe I (UV 12) at 2355.9 Å) newly recognized as the result of the well-known Mg II - Fe I pump that produces the UV 44 lines above 2300 Å. The first involves the pumping of a new level of Cr II by hydrogen Lyman-alpha, the details of which are given in Ref. 3. The other two processes explain lines whose identities have long been suspected, but whose excitation mechanisms were unknown. A strong line at 2416 Å had been tentatively identified with Ni II (UV 20) (Ref. 4), but no plausible excitation mechanism was known. We now believe that the upper level of this line is radiatively excited by the Si II (UV 0.01) lines near 2335 Å, through a coincident Ni II (UV 20) line. The situation is similar regarding the Si I (UV 11) line at 2516 Å (Ref. 5), whose upper level we believe to be populated by the 2070 Å Fe II line pumping a coincident Si I (UV 1) line. The Fe II line is itself a fluorescent line whose upper level is pumped by Lyman-alpha, so that the Si I line can be, in the end, attributed to Lyman alpha as well.
Table 1.

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* = the transition has not been assigned a multiplet number in C. Moore’s tabulations (Ref. 9); see Carpenter et al. (Ref. 2) for transition information.
3. FE II SELF-FLUORESCENCE PROCESSES

The very large number of Fe II lines blanketing the 2000 - 3200 Å spectral region almost guarantee the existence of this special case of fluorescence, in which a ion pumps itself to produce emission lines from levels that are too high to be populated collisionally. Carpenter et al. (Ref. 3) identify the first observed examples of this phenomenon in cool giants. They list four levels in Fe II that appear to be populated by such a mechanism in the chromosphere of Gamma Crucis.

The processes that populate the first two levels are illustrated in Figure 1, which shows two separate lines from UV 1 (at 2631 and 2599 Å) pumping UV 171 and UV 265 lines to produce a total of 5 fluorescent lines from UV 158, UV 171, and UV 207.

Figure 2 illustrates a process in which two different emission lines, from two different multiplets (UV 1 and UV 3 at 2628 and 2539 Å, respectively), pump the same upper level to produce two emission features at 2741 and 2435 Å, from UV 260 and UV 180, respectively.

Finally, Figure 3 shows one additional possible self-fluorescence process. There appear to be 3 distinct pumps through 3 separate lines for one upper level. However, only one fluorescent product is visible in the Gamma Crucis spectrum and we cannot be as confident about this process as the other two. The line we do see, from UV 161 at 2482 Å, is quite strong, but the next strongest transitions from this upper level at 2827 Å (UV 131) and 2827 Å (UV 114) are not seen. However, the gf-values for the latter two lines are more than 1.5 orders of magnitude weaker than for the UV 161 line and it is reasonable for them to be too weak to be observed.

These Fe II self-fluorescence processes are summarized in Table 2.

<table>
<thead>
<tr>
<th>Fluorescent Features</th>
<th>Pumped Transitions</th>
<th>Pumps</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe II (UV 180 &amp; UV 265)</td>
<td>Fe II (UV 203 &amp; UV 165)</td>
<td>Fe II (UV 1 &amp; UV 3)</td>
<td>Both lines pump same upper level</td>
</tr>
<tr>
<td>2437.9</td>
<td>2628.6</td>
<td>2628.3</td>
<td></td>
</tr>
<tr>
<td>2741.4</td>
<td>2359.1</td>
<td>2359.1</td>
<td></td>
</tr>
<tr>
<td>Fe II (UV 161)</td>
<td>Fe II (UV 161 &amp; UV 198)</td>
<td>Fe II (UV 33, uncertain)</td>
<td></td>
</tr>
<tr>
<td>2482.1</td>
<td>2493.2</td>
<td>2493.2</td>
<td></td>
</tr>
<tr>
<td>2768.4</td>
<td>2768.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (UV 207)</td>
<td>Fe II (UV 203 &amp; UV 165)</td>
<td>Fe II (UV 1)</td>
<td>single line; blended with UV 33 line</td>
</tr>
<tr>
<td>2497.8</td>
<td>2599.5</td>
<td>2599.4</td>
<td></td>
</tr>
<tr>
<td>2493.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (UV 158)</td>
<td>Fe II (UV 171)</td>
<td>Fe II (UV 1)</td>
<td></td>
</tr>
<tr>
<td>2538.8</td>
<td>2631.0</td>
<td>2631.0</td>
<td></td>
</tr>
<tr>
<td>2548.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (UV 171)</td>
<td>Fe II (UV 171)</td>
<td>Fe II (UV 1)</td>
<td></td>
</tr>
<tr>
<td>2619.1</td>
<td>2631.0</td>
<td>2631.0</td>
<td></td>
</tr>
</tbody>
</table>

Reference: Carpenter et al. 1988 (Ref. 2).
Figure 1. Partial Grotrian diagram illustrating 2 Fe II self-fluorescence processes which pump two separate levels of Fe II to produce a total of 5 fluorescent line products.
4. LYMAN-ALPHA/Fe II FLUORESCENCE PROCESSES

The most prolific pump in the outer atmospheres of these stars is by far the hydrogen Lyman-alpha line near 1216 A. This line is very broad in the non-coronal stars, extending over approximately 3 A, for example, in the N-giant Gamma Crucis and has over two dozen coincidences with Fe II transitions with well-populated lower levels. At typical chromospheric temperatures on the order of 10,000 K, Fe II levels up to about 6.0 eV can be populated by collisions. Many lines are seen from these levels, which include the UV multiplets 1-5, 32-36, and 60-64. The various Lyman-alpha pumps however are able to populate a number of energy levels which lie well above these collisionally-excited states, up to an excitation energy of over 13 eV. In the UV we observe both direct decays from these high-energy levels and secondary cascades from intermediate levels populated by some of the direct decays. Decays from these high-lying levels also assist in the population of the collisionally-excited levels below 6 eV, so that many of the lines from relatively low-lying upper levels are, in part, powered by Lyman-alpha photons as well.

Many of the Lyman-alpha/Fe II fluorescent features seen in these stars have been recognized for some time. In particular, several UV multiplets in the region above 2800 A were identified by Brown, Ferraz, and Jordan (Ref. 5) and Johansson and Jordan (Ref. 7) as originating from Lyman-alpha pumping processes. The UV 380, 399, and 391 lines are produced by secondary cascades from the directly pumped level. In addition, Johansson and Jordan (Ref. 7) identified several features near 1300, 1870, 2404, 2430, and 2500 A as direct decays from pumped levels and Jordan (Ref. 8) has added a line near 1366 A.

Carpenter et al. (Ref. 2) have recently identified 9 new fluorescent products in the spectrum of Gamma Cru, which result from both previously recognized and new Lyman-alpha pumps. One of these is a secondary cascade (UV 363 at 2537 A), while the rest are direct decays from the pumped levels. One of the direct decays is from a newly identified level of Fe II at 13.00 eV that produces a line at 1360 A (see Ref. 3 for details). The remaining lines at 1369, 2415, 2457.0, 2457.1, 2430, 2439, and 2448 A involve previously known energy levels. None of these transitions has been given a multipllet number in Moore (Ref. 9), but the specifics of the transitions are given in Ref. 2.

Figure 4 is a partial Grotrian diagram for Fe II which shows the transitions which produce lines seen in the UV spectra of non-coronal stars. It includes the lines pumped and produced by the Lyman-alpha fluorescences as well as the lines originating from upper levels populated primarily by collisions. The electronic configurations and terms are indicated on the figure, but the terms have not been broken down into levels to avoid the production of an unreadable figure! Transition labels indicated with four digits are individual lines or sets of lines, with the digits specifying wavelength in angstroms. Transition labels preceded by a "UV" indicate UV multiplet numbers, i.e., sets of lines. The upward transitions pumped by Lyman-alpha are grouped together so that multiple transitions to the same term can be represented by a single line. "IR" indicates an infrared line or multiplet. This one figure shows the origin of about 70% of all the lines seen in the UV spectrum of non-coronal stars!

5. SUMMARY

Selective radiative excitation of spectral lines through line fluorescence processes are a prominent line formation mechanism in the outer atmospheres of late-type giant and supergiant stars. All the emission lines of Fe I, Ni II, Si I, Cr II, Co II, CO, as well as numerous lines of O I, S I, Cr II, and lines from high-lying levels of Fe II are seen in the spectra of non-coronal stars solely because of these processes. Even the "collisionally-excited" Fe II emission lines arising from levels below 6 eV, which dominate the spectral region above 2200 A, contain some contributions from the Lyman-alpha. This may help explain the very high opacity of these latter lines and thus the "line leakage" observed in these spectra (Ref.'s 2 and 10).

This work was supported by grants NASA-797 and NAS-29337 from the National Aeronautics and Space Administration to the University of Colorado.

6. REFERENCES

Figure 2. Partial Grotrian diagram illustrating a Fe II self-fluorescence process in which 2 separate lines pump the same level of Fe II to produce 2 fluorescent lines.

Figure 3. Partial Grotrian diagram illustrating a possible Fe II self-fluorescence process which requires 3 separate pumps to excite one Fe II level and produces a single fluorescent feature near 2482 Å.
### Table 3

**Fe II FLUORESCENT LINES PUMPED BY LYMAN ALPHA**

<table>
<thead>
<tr>
<th>Fluorescent Features</th>
<th>Pumped Transitions</th>
<th>Pumps</th>
<th>Reference for Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIRECT DECAYS FROM PUMPED LEVEL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (#) 1289.1 A</td>
<td>Fe II (#) 1216.6</td>
<td>H I (UV 1) 1215.7 A</td>
<td>Johansson &amp; Jordan 1984 (Ref. 7) all weak in Gamn Cru</td>
</tr>
<tr>
<td>Fe II (#) 1299.3</td>
<td>Fe II (#) 1215.6</td>
<td>1215.7 A</td>
<td></td>
</tr>
<tr>
<td>Fe II (#) 1299.4</td>
<td>1216.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (#) 1360.2</td>
<td>Fe II (#) 1215.5</td>
<td>H I (UV 1) 1215.7</td>
<td>Carpenter et al. 1988 (Ref. 2)</td>
</tr>
<tr>
<td>Fe II (#) 1366.4</td>
<td>Fe II (#) 1214.7</td>
<td>1215.7</td>
<td>Jordan 1988 (Ref. 8); Carpenter et al. 1988 (Ref. 2) (1368.8 weak in Gamma Cru)</td>
</tr>
<tr>
<td>Fe II (#) 1368.8</td>
<td>1214.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (#) 1869.5</td>
<td>Fe II (#) 1215.2</td>
<td>1215.7</td>
<td>Johansson &amp; Jordan 1984 (Ref. 7)</td>
</tr>
<tr>
<td>Fe II (#) 1872.7</td>
<td>1215.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (#) 2407.2, 2431.0</td>
<td>Fe II (#) 1216.0</td>
<td>H I (UV 1) 1215.7</td>
<td>Johansson &amp; Jordan 1984 (Ref. 7)</td>
</tr>
<tr>
<td>Fe II (#) 2415.19, 2457.10</td>
<td>Fe II (#) 1216.3</td>
<td>1215.7</td>
<td>Carpenter et al. 1988 (Ref. 2)</td>
</tr>
<tr>
<td>Fe II (#) 2404.0, 2408.5</td>
<td>Fe II (#) 1214.1</td>
<td>1215.7</td>
<td>Carpenter et al. 1988 (Ref. 2)</td>
</tr>
<tr>
<td>Fe II (#) 2448.1</td>
<td>Fe II (#) 1216.5</td>
<td>1215.7</td>
<td>Carpenter et al. 1988 (Ref. 2)</td>
</tr>
<tr>
<td>Fe II (#) 2457.0</td>
<td>Fe II (#) 1216.2</td>
<td>1215.7</td>
<td>Carpenter et al. 1988 (Ref. 2)</td>
</tr>
<tr>
<td>Fe II (#) 2504.9, 2506.8</td>
<td>Fe II (#) 1217.8</td>
<td>1215.7</td>
<td>Johansson &amp; Jordan 1984 (Ref. 7) 2504.9 blended with UV 33</td>
</tr>
<tr>
<td>Fe II (#) 2506.4, 2508.3</td>
<td>1218.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SECONDARY CASCADES FROM PUMPED LEVELS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II (363) 2537.1</td>
<td>Fe II (#) 1215.7 +/-2</td>
<td>H I (UV 1) 1215.7</td>
<td>Carpenter et al. 1988 (Ref. 2)</td>
</tr>
<tr>
<td>Fe II (UV 380) 2817-2856</td>
<td>Fe II (#) 1215.7 +/-2</td>
<td>H I (UV 1) 1215.7</td>
<td>Brown, Ferraz, &amp; Jordan 1981 (Ref. 6)</td>
</tr>
<tr>
<td>Fe II (UV 399) 2824-2859</td>
<td>Fe II (#) 1215.7 +/-2</td>
<td>H I (UV 1) 1215.7</td>
<td>Johansson &amp; Jordan 1984 (Ref. 7)</td>
</tr>
<tr>
<td>Fe II (UV 391) 2839-2852</td>
<td>Fe II (#) 1215.7 +/-2</td>
<td>H I (UV 1) 1215.7</td>
<td></td>
</tr>
</tbody>
</table>

# = the transition has not been assigned a multiplet number in C. Moore's tabulations (Ref. 9); see Carpenter et al. (Ref. 2) for transition information.
Figure 4. Partial Grotrian diagram for Fe II showing the transitions which produce lines seen in the UV spectra of non-coronal stars. The transitions pumped by Lyman-alpha are shown by dot-dashed lines, while downward transitions (i.e. observed emission lines) are indicated by solid lines. See the text for further details.
Fell LEVEL POPULATION IN LUMINOUS VARIABLE STARS

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ABSTRACT
We have derived the overall Fell level population in the luminous variable stars KQ Pup and AC Car using the Self Absorption Curve method of analysis of the optical and UV Fell emission lines. We found that most levels are nearly populated according a Boltzmann-type law with excitation temperatures of 6500 and 7500 K for KQ Pup and AC Car respectively. For KQ Pup there is evidence of selective excitation processes and dielectronic recombination in the level population. The importance of the study of the Fell spectrum as diagnostics of the physical processes in astrophysical objects - from stellar chromospheres to distant galaxies - is finally discussed.

Keywords: line formation, atomic level population, stars: emission line.

1. INTRODUCTION
Absorption and emission lines of Fell have been identified in a wide variety of different astrophysical objects, and their strength can be used as a diagnostic of the physical conditions in the solar and stellar atmospheres, in stellar winds, as well as in distant active extragalactic objects. The Fell Problem has inspired a large amount of new researches, both observational and theoretical, and stimulated new works on the atomic parameters of this ion. The high lights of the problem were discussed during the international conference on the "Formation of Fell Lines Outside LTE" held in 1986 (ref.1). This ion is present in the UV with a very large number of resonance, low and high excitation lines, and several attempts were recently made to develop ad hoc techniques of analysis, such as curve-of-growth type methods, and spectral synthesis. We shall illustrate here some interesting results obtained using these techniques, and their usefulness in deriving the Fell level population in the stellar envelopes and in the interpretation of UV spectra.

2. THE VV CEP STAR KQ PUP
Several cool variables display a rich Fell spectrum in the UV. Typical examples are Mi, the symbiotic stars RR Tel and CH Cyg, the ζ Aur/VV Cep variables ζ Aur, Σ Sge, 51 and 52 Cyg. In these objects Fell lines are probably formed in the cool star's wind ionized by the UV photons from the hot companion. The VV Cep star KQ Pup (Boss 1982) displays a very rich Fell spectrum in its near and far-UV (refs.2-3). Altamore et al. (ref 3) identified more than 300 Fell lines with absorption and/or emission components belonging to transitions of a wide range of excitation potentials (EP) and oscillator strengths. We have analyzed the Fell emission lines in the high resolution IUE spectra of KQ Pup using the Self Absorption Curve (SAC) method developed by Friedjung and Muratorio (ref.4). The SAC describes the self absorption effects on the emission line intensity as a function of the line opacity. In the plots abscissae are log(gf) and ordinates are log(I/O_0) + Ω/λ. Here I is the emission line intensity, λ the lower and upper excitation potentials of the transition, Ω is 5040/Tex, where Tex is the Fell level excitation temperature which describes the relative level population. Hence the SAC method is similar to the classical curve-of-growth method, except that in this case the optically thin portion of the curve is horizontal.

Friedjung and Muratorio (ref.4) have computed several theoretical curves corresponding to different structures of the emitting region, including low and high velocity wind, and wind confined in a disk. Figure 1 shows the self-absorption plot for the UV multiplets 61, 62 and 63 in KQ Pup, fitted by a low velocity wind curve. The other multiplets were horizontally and vertically shifted to overlap on the curve of Fig.1. The horizontal shifts give the relative population N'/g' of the lower levels, while the vertical shifts provide the relative population N''/g'' of the upper levels.

Figure 1. The self absorption curve for the FeII UV multiplets 61-63 in KQ Pup. The full line is the theoretical curve for emission line formed in a uniform wind.

From the shifts we have derived the relative population of the lower (0 to 7 eV) and upper levels (14.8 to 12 eV) of FeII. The results are shown in Figure 3 where the diagrams relative to the lower and upper levels are overlapped. The figure describes the population distribution of ionized iron from 0 to 12 eV, and this is the first time that the level population of a ion in a stellar envelope is known in such a wide EP range. Evident is in the figure that most of the levels are populated according to a Boltzmann-type law with a mean excitation temperature of about 6500 K. For instance a level near 8 eV is $10^{-6}$ to $10^{-7}$ times less populated than the ground level. Several levels significantly deviate from the 6500 K relation. In most cases this should be attributed to fluorescence mechanisms of level excitation as discussed in ref.1. A similar effect was in fact observed in many other astrophysical objects, such as the chromosphere of cool stars and in symbiotic stars. The uppermost FeII levels are clearly overpopulated with respect to the Boltzmann law. We think that this is probably due to the contribution of dielectronic recombination of FeII. This ion is in fact present in the UV spectrum of KQ Pup. The narrowness (40 km/s) of the FeII lines may suggest that these lines are formed in the low velocity wind of the M supergiant. Our results thus imply that the wind is (partially) ionized by the radiation of the hot companion of the M star, and that 6500 K is a kind of equilibrium temperature of the gas.

Figure 2. The FeII level population in the envelope of the UV Cep star KQ Pup. Ordinates are log of the relative level population $N/\bar{N}$. A 6500 K distribution law is indicated.

3. THE P CYGNI STAR AG CARINAE

The most luminous blue stars, such as the P Cygni stars and the Hubble-Sandage variables (belonging to the category of the Luminous Blue Variables LBV) frequently show in their optical spectrum a large number of FeII lines in emission, often with a complex profile. These lines should be formed in cool parts of their atmospheric and circumstellar envelopes, probably as a result of intense processes of mass ejection from the central star. The IUE spectra of these stars are generally characterized by a large amount of 'shell' FeII absorption lines which strongly affect their UV energy distribution. Typical cases are represented by the galactic stars P Cyg, n Car and AG Car, by the Magellanic Cloud stars S Dor and R 127, and by the Hubble-Sandage variables, all showing a combination of hot and cool spectral features which makes the interpretation of their optical and UV spectra quite a difficult job. In order to face quantitatively with this problem, we have started to analyze the optical FeII emission lines in some galactic and Magellanic Cloud stars, and computed the synthetic spectra in the IUE ultraviolet. Some examples are described in the paper of Maratario and Friedjung (ref.5). Here we discuss the results for AG Car.

AG Car is a galactic LBV which in recent years underwent a dramatic spectral change from Aeq to Of associated with a large fading of the visual magnitude but without a significant change of the bolometric magnitude (refs.6-7). The UV spectrum of AG Car is dominated by a large amount of FeII lines with P Cygni profile, strongly blended each others, which substantialy modify the UV energy distribution of the star.
4. CONCLUSIONS

So far the works on the ionized metal lines in the emission line spectra of peculiar variables have suffered of the poor knowledge about the excitation and ionization processes and of the level population distribution. We have shown here that in two rather extreme cases the distribution is quite close to a Boltzmann-type one, although important deviations are present for several individual levels. This is a fundamental basis for the next step which is the computation of theoretical spectra, which include the 'line blocking' of FeII lines in the stellar winds, and their comparison with the low resolution ultraviolet spectra of luminous variable stars especially in distant galaxies. This is a necessary way to make reliable interpretation of the space observations of faint stars.

On the other hand the results in figures 2 and 3 are basic to understand the physical processes of line excitation outside the thermal equilibrium as in the external atmospheric envelopes. Certainly a better knowledge of the atomic parameters of FeII (and of other similar ions) and the availability of high S/N ultraviolet spectra - such as those which will be provided by the Hubble Space Telescope - should give in the future precious information on the physics of the envelopes of stars and active galaxies.

We are grateful to O. Stahl and B. Wolf for having placed at our disposal their spectrum of AG Carinae.

5. REFERENCES

IDENTIFICATION OF NEW FLUORESCENCE PROCESSES IN THE UV SPECTRA OF COOL STARS FROM NEW ENERGY LEVELS OF Fe II AND Cr II

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ABSTRACT

We present two new fluorescence processes operating in atmospheres of cool stars, symbiotic stars and the sun and identify two emission lines, at 1347.03 and 1360.17 Å, as fluorescence lines of Cr II and Fe II. The lines are due to transitions from highly excited levels, which are populated radiatively by the hydrogen Lyman alpha line due to accidental wavelength coincidences. Three new energy levels, one in Cr II and two in Fe II, are reported.

Keywords: Atomic Energy Levels, Fluorescence, Line Identifications, Cool Stars

1. INTRODUCTION

Far ultraviolet spectra of cool stars show a number of emission lines in the wavelength region 1200 - 2000 Å. At a very early stage of the analysis of low resolution spectra, it became obvious that the identities of the lines were not easily established. The explanation of the strong O I lines around 1300 Å as fluorescence lines, pumped by Lyman beta of hydrogen, suggested that the lines in the Lyman series could be a powerful source for photoexcitation.

Based on an extended laboratory analysis of Fe II (Ref. 1), Brown, Ferraz and Jordan (Ref. 2) discussed the possibilities of photoexcitation of Fe II in cool stars due to close coincidences between some new Fe II lines and Lyman alpha. This was later confirmed by Johansson and Jordan (Ref. 3), who identified a large number of emission features in IUE spectra of cool stars as fluorescence lines of Fe II. In particular, there was one line at 1869 Å, which is quite prominent in many IUE spectra, not only of cool stars (cf. Ref. 4). It happened to coincide with an unclassified Fe II line, tabulated in Ref. 1. The line was identified by Johansson and Jordan (Ref. 3) under the assumption that it shared its upper level with another Fe II transition, which had about the same wavelength as Lyman alpha. This case of Lyman alpha pumping differed from other fluorescence processes in that it led to the discovery of a new energy level in Fe II at 13.4 eV.

In the present paper we give two new examples of “astro-atomic spectroscopy”, where unidentified emission lines in cool stars have contributed additional information to the analysis of laboratory spectra in the search for new energy levels. The discoveries were made in connection with an extensive analysis of the ultraviolet spectrum of Gamma Crux by Carpenter et al. (Ref. 5), where a number of other new fluorescence processes and lines were also found. These are discussed in a companion paper by Carpenter and Johansson (this volume, Ref. 6). Two lines at 1347 and 1350 Å have now been identified as transitions in Cr II and Fe II, whose upper levels are excited by Lyman alpha. Both lines appear also in the solar spectrum as strong features (Ref. 7). This is the first time Cr II is proposed to contribute to the fluorescence spectrum of cool stars below 2000 Å.

2. IDENTIFICATION OF THE 1347 Å FEATURE

Three lines around 1350 Å in the spectrum of Gamma Crux and other cool stars are also present in the solar spectrum, where they show an unusual spatial distribution (Refs. 7,8). Jordan has in Ref. 8 given tentative identifications for the features at 1360 and 1366 Å, but there is no plausible explanation for the line at 1347.03 Å.

There is a line at 1347.04 Å in the laboratory spectrum of Cr II (Ref. 9), that has been assigned to the 3d5 sGj/2 - 3d4(5D)5p FQ/2 transition. The upper level may be photoexcited by Lyman alpha in a transition from 3d4(5D)4s DQ/2 at a wavelength of 1215.76 Å, which is only 0.09 Å larger than the rest wavelength of Lyman alpha. The calculated oscillator strength for the pumped transition is -1.76 (log gf). (All calculated values of oscillator strengths and energy levels in this paper are from new theoretical calculations by Kurucz (Refs. 10,11)). For the fluorescence line at 1347.03 Å the log-gf value is -1.28. The next strongest laboratory line (log gf = -1.51) from the 5p FQ/2 level appears at 1615.64 Å, which is 0.09 Å larger than the rest wavelength of Lyman alpha. The calculated oscillator strength for the pumped transition is -1.76 (log gf). (All calculated values of oscillator strengths and energy levels in this paper are from new theoretical calculations by Kurucz (Refs. 10,11)). For the fluorescence line at 1347.03 Å the log-gf value is -1.28. The next strongest laboratory line (log gf = -1.51) from the 5p FQ/2 level appears at 1615.64 Å, which is a line in the spectrum of Gamma Cru at 1615.66 Å, primarily assigned to multiplet 2.01 of C I. These are the three strongest transitions from the 5p FQ/2 level in the ultraviolet region. The fourth largest gf value (log gf = -2.5) in this region belongs to the transition to 3d4(5D)4s sDj/2 at 1338.23 Å. This line is observed in the
The atomic structure of Cr II is quite similar to the structure of Fe II as regards the 3d^8 nl system. The 3d^8 core of Cr III has exactly the same set of spectroscopic terms as the 3d^9 core of Fe III, since ten 3d electrons make up a closed shell. The 4F level of 3d^9(4)D1sp in Cr II, which is pumped by Lyman alpha, belongs to the same category of levels as the 5p levels, which are found to be pumped in Fe II (Ref. 3). The pumped transition is in both cases a 4s-5p transition. The most probable decay from 5p is down to 5s, which means that the strongest fluorescence lines in both elements, due to this particular process, should occur in the infrared region. A number of strong 5s-5p lines of Fe II has been observed in various emission line objects.

3. IDENTIFICATION OF THE 1360 A FEATURE

The line at 1360.17 A has been observed in spectra of cool stars and other objects, e.g., RR Tel (Ref. 4) and the sun (Ref. 7). A line with the same wavelength was reported in a laboratory investigation of iron at the Vatican Observatory (Ref. 12) in 1965. This line was included by Kelly and Palumbo in their compilation of atomic lines below 2000 A (Ref. 13) and was assigned to a strange IS-forbidden transition a^5D(7/2) - x^5D(7/2), which has a matching predicted wavelength but a calculated oscillator strength of -9.6 (log gf). This identification was adopted in the recent line list of the solar spectrum (Ref. 7). However, Jordan (Ref. 2) has proposed another transition in Fe II as a possible candidate for the 1360 A line. Since the classification suggested in Ref. 13 is very unlikely we will discuss the identification given by Jordan more in detail. The proposed 3d^9 a^5D(7/2) - 3d^9(4)F4p b^5/2 transition has a calculated log gf value of -4.38 and a predicted wavelength at 1360.16 A. The upper level is supposed to combine strongly (log gf=0.240) with the F^5/2 level of the corresponding 4s subconfiguration, i.e. 3d^9(4)F4s b^5/2, which is confirmed by a strong laboratory line at 2515.12 A. However, there is no line observed at this wavelength in the spectrum of Gamma Cru, which makes the proposed identification for the 1360 A line doubtful. In addition, there is no way to excite the upper level by Lyman alpha pumping.

We propose that the line at 1360.17 A is assigned to a transition from a previously unknown level of Fe II. We have used the same technique as Johansson and Jordan (Ref. 3) applied to the 1859 A line, discussed above. We assume that the 1360 A line results from Lyman alpha pumping. The difference in wavelength between Lyman alpha and the 1360 A line matches perfectly the difference in energy between the b^5/2 and b^5/2 levels of Fe II. That gives us a tentative level at 104907.7 cm^{-1} with J=7/2. In this energy range there are two unknown levels with J = 7/2, which both belong to the 3d^94s4p configuration. One of them is a 4F level and the other one a 4F level. The 3d^9(4)D1sp(4)F^5/2 level is predicted to be located at 104595 cm^{-1} and should have three strong transitions in the ultraviolet region. These are combinations with b^5/2 (log gf=-1.45), b^5/2 (log gf=-1.70) and b^5/2 (log gf=-1.91). The corresponding wavelengths should be 1215.502, 1215.067 and 1360.178 A. The two latter lines are observed in the laboratory spectrum, while the line at 1215.502 is masked by Lyman alpha. In the stellar spectrum we only expect the line at 1360.178 A to be observed while the other two should be obscured by Lyman alpha. This means that there are two pumping transitions available for the upper level to be photoexcited by Lyman alpha in stellar atmospheres.

This fluorescence process represents a case, where two pumping transitions result in one observed fluorescence line. The few lines seen in the laboratory spectrum from the new energy level is quite unique in a complex atom but in full agreement with the results of the theoretical calculations. We should expect the same behaviour for the other fine structure levels of the 3d^9(4)D1sp(4)F term. We have found the F^5/2 level at 105407.3 cm^{-1}. This is 327 cm^{-1} above the predicted position, which agrees with the deviation (observed-calcualted) of 312 cm^{-1} for the J=5/2 level. The only lines we find in the laboratory spectrum from the J=5/2 level are combinations to b^5F and b^5D levels, i.e. the same as for the J=7/2 level. However, in this case the transitions from b^5F appear below 1211 A, i.e. too far from Lyman alpha for an efficient pumping, which may explain why we cannot see the transition to b^5D at 1352.73 A in the stellar spectrum.

4. SUMMARY

The identification of two emission features in the ultraviolet spectra of cool stars have confirmed one new energy level in Cr II and yielded a previously unknown level in Fe II. The emission lines at 1347 and 1360 A appear in the spectra of cool stars and the sun as a result of a selective excitation by the Lyman alpha line in hydrogen. These new fluorescence processes imply the need of atomic data even for highly excited levels in singly ionized atoms for the interpretation of spectra of cool stars.

5. REFERENCES


PERIODIC MODULATION OF THE ATMOSPHERE OF ALPHA ORIONIS


ABSTRACT

Alpha Orionis (Betelgeuse; M2 lab) has been monitored with IUE since 1984. Discovery of a 420-day periodic modulation of the flux in the optical and ultraviolet continua, and in the Mg II h and k line emission cores suggested that periodic photospheric pulsations were present from 1984-1986 (Ref. 1). This behavior continues through 1987. However, the general flux level of the ultraviolet continuum and the Mg II lines is decreasing, and the amplitude of the variation may be reduced. These decreases may be the emerging signature of an additional longer period. The density sensitive C II diagnostic, \( \lambda 2325.4/\lambda 2328.1 \), indicates the chromospheric densities range between \( \log N_e (\text{cm}^{-3}) = 8.7 \) and 9.5, but periodicities are not yet evident.

**Keywords:** Chromospheres, Mass Loss, Pulsation, Supergiants, Star: Alpha Ori.

1. INTRODUCTION

Because of the long life of the IUE, it has been possible to discover significant astrophysical phenomena that might otherwise have remained undetected. Alpha Orionis (Betelgeuse), a red supergiant star classified as M2 lab, has been monitored intensively since 1984 with IUE. The 420-day modulation discovered (Ref. 1) in Alpha Ori's ultraviolet (\( \lambda 3000 \)) continuum, the Mg II h and k line emission cores, and the optical (\( \lambda 4530 \)) continuum during 1984-1986 appears to result from radial pulsation that can heat and extend the atmosphere of this low gravity star, and perhaps initiate the mass flow.

The mechanisms of mass loss for luminous stars remains a perplexing problem in astrophysics, and the discovery of pulsations in Alpha Ori and other stellar populations (see, for instance, Ref. 2) may provide the important clues to the physics of driving a stellar wind.

Recent high precision measurements of the photospheric radial velocity of Alpha Ori during the 1984-1987 seasons show (Ref. 3) a periodicity of 420 ± 20 days which is anti-correlated with the ultraviolet continuum variations, as is true for many other radial pulsators. The pulsation semi-amplitude has values between 1 and 2 km s\(^{-1} \) which are in harmony with the predictions made (Ref. 1) based on the light curves of other pulsators and theoretical calculations. The amplitude of the light variations decreased from 1984 through 1986 (Ref. 1), and the photospheric velocity variations also were reduced through the 1987 observing season (Ref. 3). Establishment of pulsation in Alpha Ori marks an important milestone for stellar physics.

Observations of Alpha Ori with IUE have continued through 1987 and 1988. Happily, the program has been approved for two more years until the summer of 1990. This paper reports measurements through 1987, and initiates the search for signatures of periodic changes in the density of the atmosphere that might be expected to result from the pulsations modulating the optical and ultraviolet continua and the chromospheric lines.

2. THE ULTRAVIOLET CONTINUUM

Broad-band measurements of the continuum centered on \( \lambda 3000 \) have been obtained from large aperture exposures with the LWP camera. These observations show a systematic decrease in the level of the ultraviolet continuum on which periodic variations are superposed (Fig. 1). The long term variation may be the appearance of a long term modulation similar to the 5.78 year light and velocity variations that were suggested by spectroscopists more than half a century ago (Ref. 4, 5).

The linear dependence of the flux has been removed (top panel of Fig. 3). The amplitude of the variation may be decreasing, but seasonal gaps in the data due to the observing constraints of the IUE may also be responsible for the lack of detectable changes.

Power spectrum analysis of the flux (see Fig. 3) reveals a period of 1.12±0.02 years for the years 1984.0 - 1988.5, This value is slightly less than the period of 1.21±0.03 years found from analysis of the continuum observations 1984.0 - 1988.0, but in better agreement with the Mg II and "B" magnitude periods at that time (Ref. 1).

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**Fig. 1:** The ultraviolet continuum of Alpha Ori in the wavelength interval $\lambda\lambda$ 2950-3050 during the period 1984.0 - 1988.05. The amplitude of the variation is much above the $\approx 6$ percent uncertainty to be expected from broad-band IUE measurements, as indicated by the error bar.

**Fig. 2:** Fluxes in the Mg II $h$ ($\lambda$2802) and $k$ ($\lambda$2795) emission cores of Alpha Ori.

**Fig. 3:** Observations of Alpha Ori 1984.0 - 1988.05 with linear dependence removed (top two panels), and the power spectra (bottom panel) of the two quantities: UV continuum ($\lambda$3000) and the Mg II $h$ line ($\lambda$2802).
3. THE Mg II LINES

The flux in the emission cores of the Mg II h (X2802) and k (X2795) lines obtained from high resolution spectra taken with the LWP camera through the large aperture are shown in Fig. 2. As noted earlier, (Ref. 1), the lines do not vary in similar fashion, perhaps due to circumstellar, or interstellar contamination, or atmospheric motions, or changing wind opacity. Because the h line appears to follow the variations of the ultraviolet continuum better than the k transition, we use the h line for period analysis (see Fig. 3). The period derived corresponds to 1.00 ± 0.02 years which agrees with our earlier results (Ref. 1), and the ultraviolet continuum measures discussed above.

4. THE C II LINES

The moderately strong C II transitions near X2335 were recognised (Ref. 6) to offer a useful density diagnostic for the atmospheres of luminous cool stars, and long (~15 min) high resolution exposures with the LWP camera through the large aperture have been obtained in order to measure the relative line strengths.

In Alpha Ori, however, and most probably other cool supergiants as well, the appearance of a variable Fe II emission feature (see Fig. 4, and also Ref. 7) severely compromises the use of two out of three identified (Ref. 5) line ratios to be used as diagnostics.

Carpenter (Ref. 7) noted, from comparison of the Alpha Ori spectrum to that of a giant star (Ref. 8), that the Fe II lines are likely to be centrally reversed in Alpha Ori. An Fe II line (X2327.301; Mult. 3) lies close to C II (X2328.133); whereas the long-wavelength component of the Fe II line is obvious in the spectrum (Fig. 4), and can be easily separated from C II by Gaussian deconvolution, the short wavelength component is not visible because it is blended with the C II transition at X2328.390. Moreover, the ratio of the fluxes in the short and long wavelength components of Fe II varies as measured in numerous spectra which are sufficiently well exposed to reveal another component of the same multiplet (X2328.035). Thus if removal of the short wavelength component of the offending Fe II line were attempted, an uncertainty of as much as ±30 percent exists in its value. Unfortunately also, the Fe II line can itself represent a fair fraction of the C II line - values of one-third are not uncommon, so that the density-sensitive ratio can easily have errors of fifty percent. These uncertainties are unacceptable, and so we have not used all three ratios, but only the one formed from X2325.4/X2328.1. The X2325.4 line is the strongest of the multiplet, making its measurement the most reliable.

The fluxes in the lines were extracted by simultaneously fitting both the continuum and Gaussian line profiles using least-square techniques. Eleven high-dispersion, large aperture spectra, acquired between 1981.02 and 1988.106, were sufficiently well exposed to be useful. The ratio, R, is shown in Fig. 5 as a function of the relative flux in X2325.4. The values of the ratio correspond to electron densities varying from log N_e = 8.7 to 0.5 cm^-3 (T_e = 3.8 and 2.1, respectively), according to the calculations in Ref. 9. The value of the ratio tends to be higher in Alpha Ori (and thus the inferred density is less) than the values derived (Ref. 10) for giant stars, α Boo, α Tau, and β Gru.

Fe II

C II

WAVELENGTH (Å)

Fig. 4: Emission lines from the density-sensitive C II multiplet near X2325 in LWP 12517 (17 Jan. 1988). The weak feature of Fe II (X2327.4, Multiplet 3) appearing shortward of X2328 is double-peaked in Alpha Ori spectra. The long wavelength component is visible (marked as Fe II) and clearly separable from the C II line (X2328.1) but the short wavelength component blends with the C II transition at X2328.1. The calibration of the observed flux was made with an arbitrary factor of 100 between high and low dispersion sensitivity.

A variation in electron density of about a factor of 0.6 is not an unexpected value from density compressions and shocks resulting from pulsations of the photosphere. The data is not yet adequate to identify a period in the density variations.

5. CONCLUSIONS

Alpha Orionis continues to provide an excellent target with which to define the physics of chromospheres and stellar winds. The existence of several periods of variability in the emissions from the star is apparent, but not yet well-defined. It may be possible to extract variations of the atmosphere in response to photospheric pulsations. These are only hinted at in the present data. With observations during the next few
years, we should be able to pin down the existence of a long term period and associated chromospheric enhancements. By also acquiring quality observations of features unique to the ultraviolet, we can also make quantitative measures of the electron density and the motions in the star's atmosphere.

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MG II LINE PROFILES OF THE MIRA S CARINAE

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ABSTRACT

A series of high-dispersion IUE observations obtained to investigate the evolution of the shock structure of the Mira S Carinae (S Car) have produced - despite very limited phase coverage - a set of five exceptionally interesting spectra of the Mg II h and k lines. The two primary findings of these observations are 1) there is significant emission from both the h and k lines at velocities of -150 km \(s^{-1}\) relative to the stellar photosphere and 2) the h-to-k ratio of the Mg II doublet remains below the theoretically predicated values of 2:1 to 1:1, and shows a smooth dependence on the optical phase. Archival studies of other Miras (e.g., R Car) indicate that S Car is not unique in possessing unusual and highly variable Mg II h and k line profiles.

Keywords: lines: profiles - shock waves - stars: emission-line - stars: Miras - stars: atmospheres

I INTRODUCTION

Until recently, very few attempts have been made to observe the Mg II resonance lines of Miras (or other evolved stars) in high dispersion. Such attempts as have been made have lacked the phase coverage that is necessary to account for the fact that Miras are long-period pulsational variables, and that the associated atmospheric changes will inevitably influence the characteristics of the Mg II line profiles. Undoubtedly, some of the difficulty of observing these stars adequately throughout the course of even one full period stems from the long timescales involved - generally on the order of one to two years. Nonetheless, vital clues regarding the formation of extended chromospheres, mass loss, and shock propagation are contained in these line profiles, especially when they are observed over a significant fraction of the pulsation cycle.

Previous IUE observations of the atmospheres of Miras and related pulsationally unstable stars (e.g., RV Tauri) have concentrated on the integrated Mg II line fluxes (obtained from low-dispersion IUE observations), and in particular their variability as a function of the optical phase (Brugel, Willson, and Cadmus 1986, and Brugel et al. 1987). Theoretical models (Bowen 1988) developed to explain the phase-coupled variability and describe the influence of the outward propagating shock on the atmosphere, are primarily concerned with explaining the integrated Mg II flux observations and at present do not attempt to describe the line profiles. Nonetheless, for at least some stars (e.g., T Cephei) the agreement between the observed and predicted integrated Mg II line flux is quite satisfactory, though for S Car the agreement is particularly poor (Brugel et al. 1987).

We have selected for a high-dispersion study this relatively short period (149 days) Mira S Carinae, which has the added attraction of an extremely high radial velocity (+284 km \(s^{-1}\)) (Willson, Wallerstein, and Pilachowski 1982). This radial velocity is sufficient to remove the Mg II emission entirely from the interstellar medium absorption, enabling us to obtain accurate line fluxes and profiles without the uncertainty associated with modelling the ISM absorption profile. S Car is also bright enough in Mg II that high resolution LWP observations can be obtained in a reasonable amount of time throughout the bulk of the shock cycle. We present these observations, as well as some preliminary interpretations, below.

II OBSERVATIONS

A series of eight low- and six high-dispersion long wavelength (1000 - 3400 Å) IUE spectra were obtained of the Mg II h and k lines near 2800 Å during November 1987. These observations, spaced one to 17 days apart (equivalent to 0.02 to 0.11 of the optical phase) and covering a total of three weeks (0.15 of the total optical cycle) are the first high-dispersion observations made with a view towards studying the phase dependence of the Mg II line profiles and emission strengths. Additional low and high dispersion spectra were obtained on 17/18 December 1987; these data are removed by about 0.3 in phase from the November observations. At the time of the final high-dispersion spectrum, the Mg II flux had decreased to essentially undetectable levels. Prior to each high-dispersion spectrum, a corresponding low-dispersion observation was obtained to provide an accurate measure of the total flux in the Mg II
Table II
S Carinae - UV Data

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R Carinae - UV Data

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† The total Mg II flux is obtained from the low-dispersion images; all fluxes are in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$. No low-dispersion images were available for R Car.

III.1 The Mg II Line Position

The observed Mg II emission lines are not seen at the stellar rest velocity, but rather shifted to shorter wavelengths by approximately 1.6 Å (assuming a stellar radial velocity of $+284$ km s$^{-1}$). There are two possible explanations for this position shift. First, the emission may be intrinsically asymmetric, with a single emission component shifted by about 150 km s$^{-1}$ towards shorter wavelengths. Alternatively, the line may be symmetric about the stellar rest velocity, with a width of about 300 km s$^{-1}$. The second hypothesis is supported by measurements of the Mg II pumped Fe I lines at 2823.3 Å and 2844.0 Å, which sample the Mg II flux at a stellar rest position of 2795.5 Å. The measured flux of the Fe I 2823.3 Å line is $9 \times 10^{-14}$ and $5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ at phases 0.32 and 0.45. Assuming an Fe I absorption line width of 0.1 Å, this implies Mg II fluxes at 2795.5 Å, of $9 \times 10^{-13}$ and $5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, which are significantly above the directly observed Mg II values, and also implies a much greater Mg II line width (of order 300 km s$^{-1}$, full width) than is directly observed (note that the variation of the Fe I line is in step with the variation of its fluorescing Mg II k line). In either case, it is apparent that there is a great deal more Mg II flux being produced in the post shock region than is observed (by about a factor of 4-5), implying a very substantial circumstellar absorption shell.

The low dispersion spectra were extracted from the spatially resolved line-by-line file provided by IUESIPS and then merged. The high-dispersion data were taken directly from the standard IUESIPS merged, extracted file. The net spectra (gross - background) were then converted to a flux scale using the absolute calibration of Cassatella and Harris 1983. Though there are possible systematic errors in the absolute fluxes, the relative flux measurements are not similarly affected since all spectra were processed with the same calibration. A very weak ultraviolet continuum was detected near 2800 Å for some of the low-dispersion observations; however, no UV continuum was detected at high-dispersion. It is thus unlikely that the continuum contributes to the line variability. We estimate that the uncertainty in the integrated flux measurements do not exceed ±10%. On the basis of the centering of the stellar image in the large aperture entrance slit during these observations, we estimate that the uncertainty in the wavelength scale is on the order of ±10 km s$^{-1}$.

III DISCUSSION

The two major results of our high-dispersion observations concern the position of the Mg II emission lines in velocity space, and the Mg II k to h line ratio. These lines (and other emissions such as the hydrogen Balmer series) are believed to form in the post-shock region of an outwardly propagating atmospheric shock wave (for a recent review see Willson and Bowen 1985).
III.2 The Mg II k/h Ratio

Our second result is the very unusual ratio (< 0.5) of the k (2795.5 Å) to h (2802.7 Å) line fluxes that is observed. The theoretically expected ratio for the k to h line ranges from 2 (for an optically thin atmosphere) to unity (for an optically thick atmosphere) and is usually observed to be within this range for stars with "normal" chromospheres. We examined the IUE archives and discovered that the Mira R Car also has a similar line ratio. To the best of our knowledge, the only other observation of a similarly unusual Mg II h/k line ratio for a non-Mira type star is that of the N-type carbon star TX Psc. The spectrum of this star has been successfully modelled in terms of a substantial cool shell surrounding the star (Eriksson et al. 1986). It is this shell which is responsible for the absorption of the underlying Mg II emission. Absorption of Mg II emission by overlying layers is a problem that has also been discussed in detail by Bernat and Lambert (1976) for the case of α Ori (M2Iab). We note that interstellar MgII cannot be responsible for the weak k line flux since the radial velocity of S Car is sufficiently large (+284 km s$^{-1}$) to shift the interstellar absorption well away from the line (see Fig. 1).

These preliminary observations also indicate that this ratio is varying smoothly from 0.43 to 0.39 as the optical phase progresses from 0.30 to 0.45 (see Figures 1 and 2, and Table II). During this same period the integrated line flux of the blended Mg II k+h line seen in low-dispersion decreases by nearly a factor of two. Observations of R Car show even more pronounced variations of the k/h ratio during the course of a shock cycle, ranging between 0.63 at phase 0.61 to 0.35 at phase 0.54. While R Car's Mg II lines are subject to absorption by the ISM, this cannot be the source of the observed variability. Even though the R Car observations were made at widely separated times, as well as the relatively poor quality of the R Car spectrum at phase 0.41, we believe that the variation is real, and supports our contention that the h/k ratio for S Car does indeed vary during a single shock cycle.

A preliminary understanding of this variability can be had as follows. The Mg II h and k line absorption profiles have slightly different wings, with the k line absorption somewhat broader. As the shock slows down relative to the circumstellar absorbers, the k line will be absorbed more strongly, resulting in a decrease in the k/h ratio. This is precisely the effect that is seen, and may yield an estimate of the amount of material in the circumstellar shell.

III.3 Search for Additional Shock Excited Lines

Finally, we note that since the Mg II is undoubtedly formed in a post-shock cooling region, one might expect to see other shock excited semi-forbidden lines of CIII] 2325Å, SiII] 2335Å, SiIV] 1385Å, OIV] 1406Å, CIII] 1909Å, OIII] 1663Å, NIII] 1750Å, and NII] 2141Å. We have carefully searched for these lines in both a deep SWP and LWP exposure, and find no evidence for any of these lines except for a very marginal (1σ) detection of the OIII] 1663Å line (5.5 $\times$ 10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$). Lack of detection of the cooler lines, formed near the same temperatures as Mg II, is somewhat surprising, and may imply that the post-shock densities are greater than the critical densities needed to quench the emission.

![Figure 1: A series of five high dispersion spectra of S Car are presented. An offset in flux of 2 $\times$ 10$^{-12}$ has been added to each successive spectrum. The vertical dashed lines mark the rest wavelength of the Mg II lines in the laboratory frame, the vertical solid lines are in S Car's rest frame.](image-url)
IV SUMMARY

Several important, yet preliminary, conclusions are drawn from the present observations. Based upon the Mg II line position and redward absorption, there appears to be a great deal more Mg II flux produced in the post shock region than is observed, implying a very substantial circumstellar absorption shell. In addition, the apparent variation of the h/k line ratio during the shock cycle may be explained by the relative motion of the shock to the overlying absorbing material. We note, however, that the apparent variation in the ratio of these lines is on the order of a 2σ result, and confirmation of this result will require additional observations obtained with higher signal-to-noise data.

The theoretical models of Bowen (1988), while they do not include the radiative transfer calculations or circumstellar absorption, and hence cannot be used to obtain line profiles, do incorporate the effects of multiple shocks and dust, and have been used to estimate line intensities for comparison with observations. However, these models must be modified in light of our observations that show that (1) most of the flux in the Mg II lines is being absorbed, implying that the cooling efficiency in the post shock region is significantly greater than currently believed; (2) the correlation of Mg II line flux with phase must also account for the change in the ratio of the Mg II h/k lines during the cycle; and (3) the models must now account for very redshifted emission, as well as the lack of blue-shifted emission. It is clear that a thorough understanding of these results will find wide applicability in understanding the outer envelopes and dynamics of cool stars other than Miras.

V ACKNOWLEDGEMENTS

These data were reduced and processed at the University of Colorado's IUE-RDAF, which is supported by NASA contract number NAGS-28731. This work was supported in part by NASA contracts NAG5-82 and NAG5-350 to the University of Colorado.

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Figure 2: An overlay – in velocity space – of S Car’s Mg II h (dashed) and k (solid) lines for the phases in Figure 1. The spectra have been shifted by the stellar radial velocity which is +284 km s\(^{-1}\). Absorption by interstellar MgII would appear close to +284 km/s in these plots. A réseau is found near +220 km/s.
THE VARIABILITY OF THE UV SPECTRUM OF THE SYMBIOTIC STAR BF CYGNI

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ABSTRACT

In this work we present the preliminary results of our monitoring of the symbiotic star BF Cygni. We have been carrying out regular observations of this system, both in low and high resolution, since July 1986 with the aim of covering a full photometric period. In order to study the long-term UV variability of the system, we have used our spectra together with archive data taken during the period 1979-1981. During the IUE lifetime, BF Cygni has undergone dramatic changes in the UV continuum and emission line fluxes. Most of the emission lines vary in phase with the continuum with deep "eclipses" near photometric phase 0. All the observational evidences support a model in which the variability of the system could be mainly due to occultations of the different emitting regions during the orbital motion.

Key Words: Symbiotic Stars; Variability

1. INTRODUCTION

BF Cygni is a low excitation "classical" symbiotic star, with weak He II lines and not discernible high excitation lines such as [Fe VII] or [Ne V] in optical spectra (Refs. 1 and 2).

The system presents a quite regular variability in the optical with an approximate period of about 757 days (Ref. 3).

The overall energy distribution indicates the presence of three different components (Ref. 4):

- a cool giant (M5 III, Ref. 5) dominating in the near-IR region,
- a hot subdwarf emitting mainly in the far-UV, and
- an ionized nebula.

In order to establish a time-dependent model, we are carrying out a regular monitoring of BF Cyg with IUE. Our observations (1986-1988) have been combined with archive data (1979-1981) to study the long term variability of the system. Unfortunately, there is a gap of about 5 years in which no data are available.

FIGURE 1

Variation of the continuum of BF Cygni in three different wavelength bands:

- - 1300 Å
- - 3000 Å
- - Visual flux computed from FES magnitude.

The observed UV minima correspond to photometric phases 0.10 (1981) and 0.07 (1987), according to the ephemeris given by Pucinskas (Ref. 3.).

2. DISCUSSION

2.1 The Continuum

The UV continuum shows large variations with different amplitudes (see Fig. 1). The largest variations occur at the shortest wavelengths (by a factor of ~10 at 1300 Å), while at longer wavelengths the amplitude is smaller (a factor of ~4 at 3000 Å) being all in phase. The observed UV minima correspond to photometric phases 0.10 (1981) and 0.07 (1987), in good agreement with the optical light curve whose ephemeris is given by Pucinskas (Ref. 3), despite the patchiness of the IUE data. However, spectra taken at approximately the same photometric phase can be quite different in different cycles.

Figure 2 shows spectra taken at different epochs. From the figure, it is apparent that the hot component of the system may be regularly eclipsed by the cool giant.

2.2 The Lines

Most of the emission lines present large variations in phase with the continuum. However, some of them (e.g. C IV 1550 Å, the O III Bowen fluorescence line at 2840 Å) have a different behaviour, as can be seen in Figure 3.

At high resolution it is worthwhile remarking the complexity of the C IV profile which shows a P Cygni-like structure (Fig. 4a). The doublet ratio is peculiar, being smaller that in the optically thick case. A similar effect has been found, for example, in Z And in outburst (Ref. 6) and R Aqr (Ref. 7).

Also, from the high resolution spectra there is evidence of phase related radial velocities variation (see Fig. 4b).

Full details of this work will be published elsewhere.
REFERENCES


FIGURE 4

a) Variation of the profiles of the C IV 1548-50 Å doublet at different dates. The vertical lines indicate the rest wavelength position.

b) High resolution spectra of the N III 1750 Å multiplet. The figure indicates that the lines experiment a velocity shift apparently related to the photometric phase of the system.

Units are 10^8 erg/cm^2 s Å. Each spectrum has been shifted 4 (Fig. 4a) and 9 (Fig. 4b) units respect to the previous one.
ABUNDANCE AND $f$ VALUES NEEDED TO INTERPRETE ADEQUATELY THE HIGH RESOLUTION I.U.E. SPECTRA

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ABSTRACT

The IUE satellite has supplied several thousands of high resolution stellar spectra which has only partially been interpreted in terms of synthetic spectra of relevant wavelength intervals. In many cases the comparison between observed and computed spectra gives poor results.

To establish the real needs to interpret correctly a high resolution IUE spectrum we perform a rough estimation of what would be the abundance or the $f$ minimal values that correspond to isolated lines in the limit of detection given by instrumental resolution.

In this way, we stress the need to develop the determination or calculation of atomic data concerning very weak spectral lines. Thus, with more complete and reliable atomic data, systematic synthetic spectra calculations could lead to better understanding the physical conditions of stellar atmospheres.

Keywords: Abundance determination; $gf$ values; stellar atmospheres; high resolution spectra

1. INTRODUCTION

In general, a quite complete interpretation of an observed stellar spectrum could be obtained by comparison with a synthetic spectrum assuming that we know the mean stellar parameters $T$, $v$, and $g$, the global (under- or over-) abundances and that we have at our disposal an appropriate atmospheric model.

This ideal situation is practically never realized, because, on the one side the goal pursued is to determine the values of many parameters like abundances, $v \sin i$, and on the other side, we are compelled to compute the synthetic spectra with inaccurate atomic data or without some of them.

Thus, anybody can be surprised to notice the disagreement between observed and computed UV spectra pointed out by several authors (Ref. 1-4).

In particular, we are prevented to analyse systematically the thousands of high resolution spectra obtained by IUE, because our knowledge of atomic data for spectral lines in the UV (1200-3000 Å) is still insufficient due to:

- uncertainties on line identifications and on deduced $gf$ values for transitions observed in laboratory experiments;
- uncertainties on theoretically (simplified theories or uncertainties in energy levels) predicted $\lambda$ and $f$ values;
- a lack of knowledge concerning other continuum-like opacity sources (i.e. autoionization transitions).

This situation lead us to recall here which are the needs on spectroscopic data in actual and future work on stellar atmosphere analysis. In particular we will estimate:

(a) the minimal abundance values that can be detected from IUE spectra, and also,
(b) the lower limits of useful $f$-values for fairly abundant species needed to interpret these spectra.

2. MINIMAL ABUNDANCE AND $f$ LIMIT VALUES

A suitable synthetic spectrum is the one that fit at least the greatest number of observed spectral features, but in practice we do not need a perfect or complete fit of all the observed features.

In other words, we do not need to know all the atomic transitions to compute a synthetic stellar spectrum: we need those transitions which produce lines that can be detected by our detectors.

Here we will simplify our analysis by considering isolated lines: the case of particular blends of a group of very weak lines of different elements will not be treated here.

High resolution IUE spectra (HRS) have a resolution of about 100 mÅ or 20 km.s$^{-1}$ at 1500 Å; Copernicus had a better one: 50 mÅ. For a sharp line spectrum ($v \sin i \lesssim 15$ km.s$^{-1}$) we hope to detect with precision spectral lines that have an equivalent width of the order of half the spectral resolution.

Let us consider the case of a weak line just saturated: its equivalent width $W_\lambda$ is given by (Ref. 5):

$$W_\lambda = R_e \sqrt{\frac{k_e}{k_e}} \Delta \lambda_D = R_e \left( \frac{\Delta \lambda}{\lambda_c} \right) \frac{N_e}{N_i} \frac{N_i}{N}\frac{N_m}{N_m}$$
where:

\[ R_f = \text{central line depletion relative to the continuum (0 < R_f < 1)} \]
\[ \Delta h = \text{element abundance relative to hydrogen} = \frac{N_i}{N_H} \]

and using,

\[ C = \frac{\alpha^2 \lambda^2}{m c^2 \alpha_c} = 8.84 \times 10^{-15} \lambda^2 \alpha_c \] (G.C.S.)

\[ \Xi = \frac{N_i}{N_j} = \frac{N_i}{N_H} = \text{relative population of level i referred to the total population of the } \text{element M} \]

(the other symbols have their usual meanings), we can rewrite \( W_\lambda \) as:

\[ W_\lambda = C R_c \Xi \alpha \] (G.C.S.)

Now, with the three following assumptions:

- the relative population of level \( i \), \( \Xi \), referred to the total population of the element \( M \) is of the order of unity in the atmospheric region where the line is formed.
- we consider a resonance line (\( f \approx 1 \)).
- the line becomes just saturated (\( R_s \approx 1 \)).

we can write:

Assuming that \( W_\lambda = 50 \text{ mA} \), we can evaluate the minimum value of the abundance that can be determined from an \( N \) stellar spectrum for example, an \( A \) star (Table 1).

In the case of a strong (and nonresonance line), the combined effect of the \( \Xi \) \( R_c \) may give 0.1; the resulting abundance values are also shown in Table 1.

These results allow us to conclude that:

- if a resonance line (\( f \approx 1 \)) is formed in an atmospheric region where practically all the \( M \)'s atoms contribute to form this line (\( \Xi \approx 1 \)) it becomes saturated (that is, \( R_s \approx 1 \)) for a minimum relative abundance of 5 \( \times 10^{-1} \);
- in the case of a strong line, this value could be of the order of 5 \( \times 10^{-1} \);
- if a line that becomes saturated, arises from an excited level such as its relative population makes \( \Xi \approx 10^{-2} \), and belonging to a fairly abundant element such as \( C, N, O, Si \) (\( \Delta h \approx 10^{-2} \)) or \( \text{Fe} \) or \( \text{Fe} \) (\( \Delta h \approx 3 \times 10^{-3} \)) then, an oscillator strength of \( f \approx 5 \), \( \Xi \approx 1 \) indicates only one optical depth belonging to the atmospheric zone of formation of some particular \( \Xi \) of the line. Moreover, the central \( \Theta_c \) of the line is generally formed in the upper photosphere and the extreme wings in the lower photosphere.

The estimation of the minimal abundance and \( f \) values which makes visible a spectral line at the \( \text{H} \text{K} \) resolution, stresses the need to consider very weak lines (less abundant species and very weak lines or very little \( f \) values) in synthetic spectro calculation to obtain a satisfactory interpretation of all the spectral features observed.

4. REFERENCES

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### Table 1

<table>
<thead>
<tr>
<th>Abundance (Ab) and f-values deduced from</th>
<th>stellar model with $T_{\text{eff}} = 10000$ °K and atmospheric layer with $T_C = 10000$ °K</th>
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<td>$C$</td>
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<tr>
<td>$\xi = 1$</td>
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<tr>
<td>minimal f</td>
<td>Ab = 1. ((-4))</td>
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<td>Ab = 3. ((-5))</td>
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### Table 2

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<tr>
<td>(\xi = 10^{-2})</td>
<td>Ab = 3. ((-5))</td>
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</tbody>
</table>
CARBON AND NITROGEN ABUNDANCE DETERMINATIONS FROM TRANSITION LAYER LINES

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ABSTRACT

For red giants we find a smooth increase in the nitrogen to carbon abundance ratio for increasing B-V as is expected for the first dredge up phase when the outer convection zone deepens. We find an average increase in the nitrogen to silicon ratio for B-V ~ 0.6 which surprisingly goes back to almost solar values for cool giants with B - V ~ 1.0. It looks as if Si would be enriched for deeper mixing contrary to expectations from standard evolution theory.

1. INTRODUCTION

In 1981 (Ref. 1) Luck and Lambert found that in supergiants and Cepheids the element abundance ratios of nitrogen to carbon were enhanced while the sum remained constant. At the same time they found that the C\(^{15}/\)C\(^{12}\) ratio was also increased as expected if mixing in the stars had brought CNO cycle processed elements to the surface. In 1981 Lambert and Ries (Ref. 2) found the same situation for giants with B - V > 0.65. In both cases they found stronger enrichments than expected from standard evolution theory. These element abundance determinations applied spectrum synthesis to reproduce the molecular bands of CN, C\(_2\), and NH. For stars with somewhat higher temperatures the infrared C and N lines were studied. Spectrum synthesis of molecular bands requires a good understanding of the temperature stratification near the temperature minimum, which may be somewhat uncertain. The infrared lines originate from rather high excitation levels and are therefore vulnerable to non LTE effects. It therefore seems good to verify the peculiar CN abundances in giants and supergiants by an independent analysis which is provided by the emission lines of the transition layers between stellar chromospheres and coronae.

Key words: Transition Layers, Giants, Carbon-Nitrogen Abundances.

2. METHOD OF ANALYSIS

2.1 Theoretical background

In an earlier paper we investigated the energy equilibrium in the lower transition layer with 30,000 K < T < 1.3 \cdot 10^5 K. The energy input \( E_{in} \) per cm\(^3\) and sec is supposed due to the damping of a mechanical energy flux \( F_m \), which means

\[
E_{in} = -\text{div} F_m = -\frac{dF_m}{dh} = \frac{F_m}{\lambda} \quad (1)
\]

where \( \lambda \) is the damping length. \( \lambda \) may vary with height \( h \) in the atmosphere. Choosing \( T(h) \) as the independent variable we approximate the height dependence of \( \lambda \) by

\[
\lambda = \lambda_0 \cdot T^\alpha \quad (2)
\]

where \( \alpha \) is a parameter which can be determined from the emission line fluxes of lines originating at different temperatures (Ref. 4). The energy loss is due to radiative losses \( E_{rad} \) per cm\(^3\) and sec which in this temperature range can be approximated by

\[
E_{rad} = \frac{dF_r}{dh} = a^2 \cdot B \cdot T^\beta \quad (3)
\]

with \( \beta = 1.9 \pm 0.1 \) and \( B \) is a constant. From \( E_{rad} = E_{in} \) we derive for the temperature stratification (Refs. 3, 4)

\[
T^{\beta+\alpha-2} = \frac{F_m^k}{\lambda_0 \cdot B \cdot \beta^2} \quad (4)
\]

and

\[
\frac{dh}{d\ln T} = \left( \frac{\beta + \alpha - 2}{2\mu E_{rad}} \right) \frac{1}{1 - \left( \frac{R_g}{\beta} \right)} \quad (5)
\]

The surface fluxes \( F_L \) of optically thin emission lines are given by

\[
F_L = C(L, T) \cdot A(\text{el}) \cdot \int n_\text{el}^2 dh = C(L, T) \cdot A(\text{el}) \cdot E_{in}(T) \quad (6)
\]

where \( C(L, T) \) depends on the collisional excitation cross section for the upper energy level of the line transition (L stands for line), \( A(\text{el}) \) is the element abundance relative to hydrogen of the line emitting element and \( E_{in}(T) = \)

by \( \int n^2 \, dh \) is the so-called emission measure. The integral has \( h_1 \) to be extended over the height interval over which the line is emitted, which corresponds to an interval in height over which the temperature changes by approximately a factor of two or over which \( \Delta \ln T \approx 0.7 \).

Comparing the line fluxes of two lines of a given element, for instance, the line flux of the C II lines at 1335 Å which originate at a layer with an average temperature around \( T_1 = 35\,000\) K and the C IV line fluxes originating at an average temperature around \( T_2 = 10^5\) K we find

\[
\frac{F_L(1335\text{Å})}{F_L(1550\text{Å})} = \frac{C(1335\text{Å}, T_1)}{C(1550\text{Å}, T_2)} \cdot \frac{\text{Em}(T_1)}{\text{Em}(T_2)} \tag{7}
\]

With

\[
\text{Em}(T_1) = \left( \frac{T_2}{T_1} \right)^{-\phi(T_1)} \cdot \phi(T_2) \tag{8}
\]

From the study of many main sequence stars and giants we find empirically the relation

\[
\text{Em}(T_1) = \left( \frac{T_2}{T_1} \right)^{-1.2 \pm 0.2} \tag{9}
\]

fits the observations best. Writing \( \phi(T_1)/\phi(T_2) = \left( \frac{T_2}{T_1} \right)^{-\beta} \). We thus obtain \( \beta - \alpha + 1 + \gamma = 1.2 \pm 0.2 \).

We can then determine the temperature dependence of the emission measures for the stars under investigation. Using solar element abundances we have plotted in figure 1 left and center part, the emission measures for main sequence and luminosity class IV stars as derived from the transition layer emission lines of C II, C IV and N V (1240 Å) originating at \( T_3 = 1.5 \cdot 10^5\) K as a function of the average temperature of the layer in which these lines originate. Within the expected measuring uncertainty (\( \approx 25\% \) for each line) these emission measures fall very well along the line given by equation (9). For our adopted solar Si abundance of log \( \text{Si/H} = -4.4 \) the emission measure calculated from the Si II lines at 1400 Å (formed at \( T_4 \approx 75\,000\) K) by means of the \( C_L(1400\text{Å}, T_4) \) which are given by Jordan and Brown (Ref. 5) came out too large which might indicate a large Si abundance. However Si II lines often give too small emission measures. This problem was discussed earlier by Hartman et al. (Ref. 6). It is suspected that the \( C_L(1400\text{Å}, T_4) \) are in error. We have applied an empirical correction of \( \Delta \log C_L(1400, T_4) = +0.5 \). This correction puts the emission measures for the Si IV lines on the same straight line with the other emission measures for all main sequence stars.

2.2 Abundance determinations for giants and supergiants

Comparing now surface line fluxes for different lines we find for instance

\[
F_L(\text{N IV}) = C(1240, T_3) \cdot A(N) \cdot \text{Em}(T_3)
\]
\[
F_L(\text{C IV}) = C(1550, T_2) \cdot A(C) \cdot \text{Em}(T_2)
\]
\[
= \text{constant} \cdot A(N) \cdot A(C) \cdot A_0(N) \cdot A_0(C) \cdot \text{Em}(T_3) \tag{9}
\]

With the ratios of the emission measures known from equation (8) and the ratios of the \( C(L, T) \) known from atomic physics (Ref. 5) the relative abundances of the elements as compared to solar abundances can be directly determined from the measured ratio of the surface fluxes \( F_L \) (which is of course the same as the ratio of the observed fluxes \( f_L \)).

Figure 1. The temperature dependence for the emission measures of solar abundance main sequence and luminosity class IV stars is shown left hand and center. We generally find \( \text{Em} \propto T^{1.2 \pm 0.2} \). In the right hand figure we show the apparent emission measures for some giants and supergiants obtained by assuming solar abundances. The apparent excess in the emission measures for the Si IV and N V lines is due to larger abundance ratios \( N/C \) and \( Si/C \). For increased abundance ratios as shown on the right hand side, the emission measures agree with the \( T^{1.2} \) relation.
3. RESULTS

3.1 The changes in the nitrogen to carbon abundance ratios

In figure 2 we compare the values $\log N/C - \log N/C_{\odot}$ for stars for which element abundances were determined by Lambert and collaborators by means of photospheric analysis with the abundance ratios determined from the transition layer emission lines. Within the limits of error we find very good agreement, though the abundance changes found by us are somewhat smaller ($\Delta \log N/C \sim -0.2$) than those found by Luck and Lambert.

![Figure 2](image)

Figure 2. The photospheric excess abundance ratios, as compared to solar abundance ratios of nitrogen to carbon, obtained by Lambert and Ries 1981 and Luck and Lambert, are compared with the ones found from the transition layer lines. Within the limits of error for both studies (shown at the lower right corner) the agreement is quite good.

In figure 3 we have plotted the $\Delta \log (N/C)$ as a function of $B-V$ for all the giants studied by us. For $B-V > 0.6$ we find a slow increase in $\Delta \log N/C$ as expected for mixing by a deepening outer convection zone when the stars expand and become cooler. We find some stars which do not strictly follow this trend. Several of these have very weak and ill defined emission lines.

![Figure 3](image)

Figure 3. The excess abundance ratios of nitrogen to carbon, as compared to solar abundances are shown for giants as a function of their $B-V$ colors. The nitrogen to carbon ratio increases smoothly for cooler stars.

3.2 The changes in the nitrogen to silicon abundance ratios

From standard stellar evolution theory we do not expect to see any changes in the silicon abundances when the stars evolve to become red giants. We should therefore be able to read off directly the increase in nitrogen abundances from the abundance ratio $N/Si$. Unfortunately the Si IV lines are generally weak and not very well defined. They sometimes appear to be blended with neighboring, unidentified lines. The results discussed here are therefore generally less reliable than those discussed in the previous section.

![Figure 4](image)

Figure 4. The excess abundance ratios of nitrogen to silicon, as compared to solar ones, are plotted as a function of $B-V$ for the stars studied here. A decreasing ratio seems to be indicated for the cooler stars but is hard to understand theoretically. Perhaps the Si IV lines are blended with other lines.

In figure 4 we show the changes in the $N/Si$ abundance ratios as a function of $B-V$. We do not see the smooth increase expected according to figure 3. The $N/Si$ ratio appears to increase at $B-V \sim 0.6$ but then decreases again for cooler stars. It seems that the silicon abundances increases even more than the nitrogen abundances. Since the Si IV lines behave somewhat unusual it is not impossible that the ionization and excitation conditions for these lines could change or that a blend with an unknown line could lead to false results. Perhaps a blend with the semi-forbidden O IV line at 1402 Å could cause the problem.

![Figure 5](image)

Figure 5. The abundance ratios of carbon to silicon as compared to the solar ones are shown as a function of $B-V$. The decrease of carbon abundances for cooler stars is obvious. If the Si IV lines appear too strong because of blending the actual decrease of the carbon to silicon ratio will be less steep than seen here.
In figure 5 we show the ratio of $C/N$ as a function of $B-V$. We see the decrease of the carbon abundances for the cooler stars as expected if CNO processed material is mixed to the surface. The decrease is steeper than expected probably due to the same increase in the Si IV line strengths as discussed in the previous paragraph.

4. SUMMARY

We have shown that relative element abundances can be determined from the emission line fluxes of lines originating in the lower transition layers. We confirm the increase in the $C/N$ ratio for cool stars found earlier by Luck and Lambert and Lambert and Ries.

Our method of analysis offers a simple way to determine $C/N$ ratios for all stars with transition layer emission lines.

ACKNOWLEDGEMENT

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5. REFERENCES

THE ANOMALOUS C IV INTENSITY RATIO IN SYMBIOTIC STARS

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ABSTRACT

The C IV λ1548.2,1550.8 resonance doublet in a few symbiotic stars exhibits anomalous line intensity ratios in which I(λ1548.2)/I(λ1550.8) < 1, or less than the optically-thick limit of unity. Both the R Aquarii-central HII region and RX Puppis exhibit this phenomena. The I(λ1548.2)/I(λ1550.8) ratio in RX Puppis was found to vary inversely with the total C IV line intensity, and with the FES-visual light, as the object declined over a five year period following a brightening in UV and optical emission which peaked in 1982. This doublet intensity behavior could be explained by a wind which has a narrow velocity range of 600 \( < \nu_{\text{wind}} < 1000 \) km s\(^{-1}\), or by the pumping of the Fe II (\( \lambda 1550.8 \)) transition. A \( \lambda 1548.2 - \lambda 1550.8 \) line by C IV λ1548.2, which effectively scatters C IV photons into the Fe II spectrum in these objects.

Key words: Symbiotic Stars, Stars, Atomic Spectra, Bowen Pumping, Stellar Winds

1. Introduction

Spaceborne ultraviolet spectroscopy in the near and far-UV has afforded investigators an opportunity to explore the complex emission line spectra of symbiotic stars. These objects are believed to be a class of interacting binary, which contain a red giant or Mira variable, and a hot companion. At optical wavelengths, the presence of an ionizing radiation source in these systems is indicated by the presence of strong nebular emission, which includes [O II], [O III], [N II], [N III] [S II], He I, He II and strong Balmer series emission. In the IUE wavelength sensitivity range, the spectra of symbiotic stars are characterized by an assortment of intercombination lines, which include C III \( \lambda\lambda 1907,1909 \), Si III \( \lambda 1892 \), N III \( \lambda\lambda 1749-1750 \), N (V) \( \lambda 1487 \), O (III) \( \lambda\lambda 1560,1666 \), O (IV) \( \lambda\lambda 1238,1401 \), as well as the permitted lines of N V \( \lambda\lambda 1239,1240 \), Si IV \( \lambda 1394 \), C IV \( \lambda 1548,1550 \), He II \( \lambda 1640 \) and He III \( \lambda 2597,2802 \). Often, the Bowen fluorescence lines of O III are also quite prominent. A number of symbiotics are sufficiently bright in the UV that high resolution spectra (\( \lambda \sim 0.1 \)A resolution) are feasible with IUE.

In at least a few of these systems, there is a growing body of evidence from the line profile structure of the strong high excitation lines of C IV, \( \lambda\lambda 1548.2,1550.8 \), and He II \( \lambda 1660 \) for the presence of high velocity winds of \( > 900 \) km s\(^{-1}\); velocities of this magnitude are probably associated with mass expulsion from the hot companion in the system, rather than the extended atmosphere of the late type star. For example, the C IV line profile structure in RX Puppis, AG Pegasi and CH Cyg exhibit broad - complex emission structure, which is probably related to mass motions in these systems, perhaps in the form of streamers or rings, formed as a result of accretion onto the hot companion.

In addition to the complex velocity structure suggested in the emission line profiles of RX Puppis, the C IV resonance doublet exhibits additional anomalous properties. Michalitsianos et al. (ref. 8) have noted a curious effect in which the C IV doublet intensities I(λ1548.2)/I(λ1550.8) in RX Puppis and R Aquarii (central HII region) are less than the theoretical optically thick limit of one. Anomalous C IV doublet intensities, where I(λ1548.2)/I(λ1550.8) < 1, have also been reported in CH Cyg, Z And and AG Peg. In the case of RX Puppis, however, the C IV intensity ratio was I(λ1548.2)/I(λ1550.8) \( \approx 0.6 \), during an enhanced phase of UV and optical emission, and became larger, acquiring a value of I(λ1548.2)/I(λ1550.8) \( \approx 1 \), as the star declined in UV and visual light over a five year period; i.e., the I(λ1548.2)/I(λ1550.8) was found to vary inversely with the C IV absolute intensity, and with the IUE-FES visual magnitude. This behavior we propose to call the "C IV Doublet Intensity Effect" (ref. 8). The anomalous C IV intensities in RX Puppis have been explained in terms of a high velocity wind which has an expansion velocity \( \nu_{\text{wind}} \) in the range \( 600 \lesssim \nu_{\text{wind}} \lesssim 1000 \) km s\(^{-1}\). As such, the broad C IV absorption trough of the \( \lambda 1550.8 \) red doublet member absorbs emission from the \( \lambda 1548.2 \) blue doublet line \( \lambda 1548.2 \), in a manner similar to that proposed for O and B-type stellar winds. However, a high velocity wind model imposes several important conditions on both the upper and lower limiting wind velocities, as well as the optical depth properties of the expanding gas.
We wish to re-examine this interpretation and consider an alternate possibility, in which the C IV doublet intensity effect could be explained if C IV l 1548.2, 2.2 μm order multiplet (multiplet 45.01) of Fe II in a Bowen type mechanism. This process is suspected to occur in RR Tel and V1016 Cyg, based upon the presence of number of fluorescently excited Fe II lines in the LWP 13200-3200 corresponding to the downward cascades of the Fe II yH4 /1/2 transition of multiplet 45.01, even though the C IV doublet ratios in these objects do not appear obviously anomalous.

The merits of both models are discussed in context with our observations of RX Puppis, which have been obtained by monitoring RX Puppis in the HIRES and LOMES mode of IUE. Recently, anomalous C IV ratios, I(1548.2)/I(1550.8) ~ 0.6 have been observed in the central HII region in R Aquarii. On the other hand, the extended HII nebulae in this symbiotic system indicates optically-thin emission in C IV, where I(1548.2)/I(1550.8) ~ 2, appropriate to a photoexcited gas. Thus, the R Aquarii system affords an opportunity to study the C IV line forming regions within its nebula in a manner not possible with other more distant, and spatially unresolved symbiotic stars, such as RX Puppis.

2. Discussion

A description of our five year IUE monitoring program of RX Puppis, and the first successful HIRES exposure of R Aquarii are described by Michalitsianos et al. (ref. 8). In Figure 1, (top: R Aquarii-HII Region; bottom: RX Puppis) we have overplotted the 1548.2 and 1550.8 lines in order to compare their structure in velocity space. The vertical arrows indicate the laboratory rest wavelength. High frequency noise was reduced by a 5-point running average which acts as a digital low-pass filter. The formal fit errors of velocity are ±0.5 km s⁻¹, the instrument velocity resolution at C IV is ~±2.0 km s⁻¹. Thus, the peak emission for both C IV members is consistent with the radial velocity of R Aquarii of V_r = -23 km s⁻¹, and V_r = +11 km s⁻¹ for RX Puppis.

2.1 Line profile Structure

The 5-point smoothing applied to the profiles ensures that high frequency noise has been removed. Therefore, the narrow emission components which survive this smoothing are likely real, and this profile structure is also evident in photowrite SWP-HIRES images of both objects. The line profile structure of the C IV doublet in RX Puppis consists of at least three distinct emission components, which have average velocity separations of ∆v ~ 40 km s⁻¹, which upon a 5-point running average were always seen redward of the rest wavelength. The velocities of these components combine to produce a broadened profile whose base width extends up to ±25 km s⁻¹ for R Aquarii-HII region exhibits similar structure but the secondary emission components obtained by double-gaussian fitting is blueward of the rest wavelength by a velocity separation ∆v ~ -50 km s⁻¹.

The velocity separation of the individual emission components which form the C IV line profile structure in RX Puppis and R Aquarii are roughly the same that the kinematics of the C IV forming regions are probably similar in both objects. If the individual C IV components correspond to discrete parcels of highly ionized gas, which are ejected from the system at roughly regular intervals of time, the predominance of redward displaced emission in the case of RX Puppis, and blueward displaced emission in R Aquarii, might reflect the orientation of ejection if the parcels are emitted successively in a one-sided stream or jet. This is consistent with high resolution radio continuum maps obtained with the Very Large Array (VLA) of RX Puppis and R Aquarii. The 6-cm radio morphology of R Aquarii and its jet clearly suggests that most of the streaming activity is confined to one side of the central object in the form of discrete knots of emission; this is reminiscent of one-sided radio tails in extragalactic jets. Recently obtained high resolution 0.01, 1.3 and 2-cm radio continuum observations of RX Puppis also indicate one-sided morphology, additionally that the relationship between radio continuum knots and C IV emitting regions could be established only with high resolution sub-parsec second imaging in the C IV lines, now only possible with HST. However, these results provide a preliminary indication establishing a correspondence between radio and UV emission from streaming material in these systems.

2.2 The C IV Doublet Member Intensities

2.2.1 The P-Cygni Profile Interpretation

In Figure 1, the shaded area formed by the superposition of the line profiles shows the velocity range over which the doublet ratio I(1548.2)/I(1550.8) is less than the optically-thick limit of unity. In the case of RX Puppis, the intensity ratio was I(1548.2)/I(1550.8) ~ 0.6, when the object was at maximum UV emission around March 1982. Over a five year period, RX Puppis gradually declined in UV line emission. In Figure 2, the I(1548.2)/I(1550.8) has been plotted against the total C IV doublet intensity for the observing epochs indicated. A linear relationship is evident between the doublet intensity ratio and UV light. In Figure 3, a similar relationship was found between I(1548.2)/I(1550.8) and the FES-visual magnitude for this period as well.

If the "doublet ratio intensity effect" is explained by a wind, a minimum wind speed of 600 to 700 km s⁻¹ is required for the doublet wavelength separation of 2.6 Å, in order for the absorption trough of the 1550.8 line to absorb emission at 1548.2. However, continuum adjacent to the C IV doublet has not been detected in long duration HRS exposures with sufficient signal to confirm the presence of broad P-Cygni structure; far-UV continuum was not detected in a 1/5-hour HRES-SWP exposure in 1987. Similar duration HRES-SWP exposures in the Aquarii-HII region also failed to detect adjacent continuum which could support this interpretation. On the
Moreover, if such a high speed wind is present, the curious absence of C IV P-Cygni structure in RX Puppis and R Aquarii places strong upper limits on $v_{\text{wind}}$ for both stars of $-4000 \text{ km s}^{-1}$, because of the limiting resolution of LORES-SWP spectra. For example, $-4000 \text{ km s}^{-1}$ P-Cygni wind profiles are detectable in LORES-SWP spectra of the planetary nebula IC 418. Accordingly, a narrow range of wind velocities of $600 < v_{\text{wind}} < 1000 \text{ km s}^{-1}$ must exist, which places tight constraints on the wind velocities, such that the $v_{\text{wind}}$ is sufficiently large compared with the doublet wavelength separation, but not large enough to be detectable in LORES-SWP spectra.

2.2.2. C IV Bowen Pumping of Fe II

Johansson (ref. 10) identified a number of Fe II emission lines of multiplet $4591$ at $\lambda\lambda 3944.20, 2454.78, 2454.00, 2452.28, 2711.15$ in HIRES-LWP spectra of the symbiotic V1016 Cyg obtained by Nussbaumer and Schild 10. These and four additional fluorescence formed lines have also been identified in RX Tel 10; they are formed by the downward cascade of the excited Fe II $y_{4671}^0$, $1/2$ level. Emission from C IV $\lambda 1548.2$ was found by Johansson (ref.10) to selectively pump the $aF_{2}/y_{1548}^0$, $1/2$ transition of Fe II in a Bowen mechanism.

Close examination HIRES-LWP spectra of RX Puppis taken in March, 1982, when the object was at maximum UV emission, and when the C IV $(\lambda 1548.2)/\lambda 1550.8$ ratio had its maximum deviation below the optically-thick limit of one, indicated only the possible presence of the second strongest line from the group identified by Johansson (ref. 10) in V1016 Cyg and RX Tel, which is Fe II $\lambda 2771.2$. The strongest member of the series Fe II $\lambda 2658.78$ was not detected. However, the HIRES-LWP exposure of 180-minutes in March, 1982 was significantly underexposed, making identification difficult for relatively weak features. Accordingly, the only manifestation of the Bowen pumping of Fe II by the blue doublet member of C IV could be the anomalous C IV intensity ratio.

Other hand, LORES-SWP ($\chi = 6\text{A resolution}$) spectra of RX Puppis and R Aquarii clearly indicate the presence of strong UV continuum emission in both objects.

Figure 1: C IV red and blue doublet lines overplotted in velocity space. The vertical arrows indicate the radial velocity of the star. The shaded area indicates the velocity range over which the doublet intensity is less than unity. The velocities shown correspond to the velocity of individual C IV emitting regions that combine to produce the broadened profile.

Figure 2: The C IV doublet intensities $I(\lambda 1548.2)/I(\lambda 1550.8)$—seven observing epochs plotted against the combined C IV emission line intensity.
Similarly, ~5-hour exposures required to detect the strongest emission lines in R Aquarii-HII region in the LWP and SWP HIRES cameras encounter similar difficulties. However, in the case of RX Puppis, IUE has sufficient sensitivity that longer exposures of ~4 hours, for a S/N ~ 10, are possible in the LWP-HIRES camera. If a direct correlation can be established between the C IV I(λ1548.2)/I(λ1550.8) intensity ratio and the strength of the fluorescent Fe II lines, the redistribution of C IV energy into the Fe II spectrum of RX Puppis would be important to establish. Because the C IV I(λ1548.2)/I(λ1550.8) ratio is related to the intrinsic UV line brightness, such a correlation could be used to determine concentration of Fe II along the absorbing pathlength during slow outbursts of the system. IUE observations are continuing to investigate this phenomena in greater detail.

3. Conclusions and Summary

The C IV I(λ1548.2,1550.8) emission lines in a select number of symbiotic stars exhibit complex profiles, suggestive of complex kinematic motions in the form of streamers, accretion rings and/or a disk. The C IV I(λ1548.2)/I(λ1550.8) intensity ratio also appears anomalous in a number of these systems, where the ratio is less than the theoretical optically-thick limit of unity. In RX Puppis, where this effect has been studied most extensively, the C IV I(λ1548.2)/I(λ1550.8) ratio appears to vary inversely with the total UV line emission.

We have suggested two possible explanations of this behavior which we propose to call the "C IV doublet intensity effect":
1) the broad P-Cygni absorption trough absorbs emission at λ1548.2, thus reducing the doublet ratio below the optically thick limit of unity during slow outbursts; the wind velocity in this case must be in the range $600 \text{ km s}^{-1}$, or
2) that owing to wavelength coincidence between Fe II and C IV, Fe II (multiplet 42,01) $^2P_{3/2} - ^4P_{1/2}$ transition can be pumped by the blue doublet C IV at λ1548.2 line 11, effectively redistributing C IV λ1548.2 photons into the Fe II spectrum in a Bowen-type mechanism.

Present IUE observations can not resolve this issue, and other exposures in the LWP and SWP cameras of IUE, or with the High Resolution Spectrophraph of IIST, will be required to probe this effect in greater depth.

References

THE IUE SPECTRAL ATLAS OF TWO NORMAL B STARS: \( \pi \) Cet and \( \nu \) Cap (125-200 nm)

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ABSTRACT

An atlas for two normal B stars, \( \pi \) Cet (HD17081, B7V) and \( \nu \) Cap (HD192432, B9.5V) is prepared in the range 125-200 nm. By means of an improved software to process the IUE images and by the coaddition of about ten available high-resolution images, the best possible resolution and signal/noise ratio are obtained. The identification of the lines is based on updated laboratory lists with a selection of the dominant contributors for each absorption line. About 80% of the measured lines have a definite identification.

Keywords: Atlas. Line identification. Ultra-violet spectra. Stars: main-sequence B-type. Stars: \( \pi \) Cet, \( \nu \) Cap

1. INTRODUCTION

Until now, only a few lists of identified lines are available for the far-ultraviolet spectrum of early-type stars, which contains so many absorption lines. Some have been published by Rogerson and Upson for five stars, from Copernicus data (see e.g. Ref.1). They do not include late main-sequence B stars, and the wavelength coverage is not complete. Other line lists were prepared by Ramella et al. (Ref.2) from IUE data in the short-wavelength region, for seven normal B stars. But their automatic procedure allowing a quick identification of prominent features, leaves a lot of weaker lines unidentified or not even detected. A reference atlas with detailed identifications appears to be indispensable, especially since the Hubble Space Telescope will provide high-resolution ultraviolet spectra. So we decided to prepare an atlas for \( \pi \) Cet (B7V) and \( \nu \) Cap (B9.5V), two slowly rotating stars, and to identify the spectral lines with the most recent laboratory line lists, instead of starting from the Kurucz and Peytremann (Ref.3) list as did Ramella et al. (Ref.2). We also intend to take benefit from the several available SWP images of these stars to extract IUE spectra of the best possible quality.

2. PROCESSING OF THE IUE IMAGES AND COADDITION OF THE SPECTRA

The spectra were derived directly from the photometrically corrected images of IUE (9 and 11 archives available in the new software, for \( \pi \) Cet and \( \nu \) Cap). We used the FASMII software of Borsenberger (Ref.4) which proceeds by a non-linear minimization to fit the data at the pixel level. Compared to the standard extraction, it gains the ability to use the data partly affected by saturation and a significant increase of the signal/noise ratios at the ends of each order. A weighted sum is made on rebinned oversampled spectra, adjusted in wavelength by an iterative procedure.
Figure 1
Identified IUE spectra of the stars $\pi$ Cet and $\nu$ Cap, in the range 147-148.8 nm
3. LINE IDENTIFICATIONS

The coadded stellar spectra were measured independently by fitting each observed line with a gaussian curve, between two limits chosen visually on the wings of each line. A total of about 2000 lines are measured for each star, most of them appearing on the spectra of the two stars with a wavelength agreement better than 0.004 nm.

The atomic data were taken primarily from the laboratory line list compiled by Kelly and Palumbo (Ref.5) and Kelly (Refs.6-7), with updated data, mainly for Fe II (Johansson, Ref.8 and Adam et al., Ref.9), Cr II (Johansson, Ref.10), and for heavy elements (Z=37 to 82) from Reader et al. (Ref.11). The list was then reduced to about 9000 lines by a careful limitation of the number of weak lines for each ion, on the basis of the observed intensities for the strongest ones.

The identification process is initiated by an intersection of the observed line list and the laboratory line list, with a tolerance of 0.01 nm. Among the multiple assignments, often found by the wavelength coincidence, we determined the principal contributor for each line, by a systematic comparison of the observed intensities in the two stars, together with the laboratory data for each detected ion. When several contributors appear equally probable, a selection of the dominant ones is done by comparison of their theoretical equivalent widths. These have been computed using gf data from Kurucz and Peytremann (Ref.3) and a typical Kurucz model atmosphere (T\textsubscript{eff}=12000 K, logg=4). For a number of ions it happens that all theoretical equivalent widths are so weak that their lines could surely not be detected; so they have been eliminated in case of wavelength coincidence.

The following species are clearly found to be present: C I, C II, C IV, N I, O I, Mg II, Al II, Al III, Si I, Si II, Si III, Si IV, S I, S II, Ca II, Ti II, Ti III, Mn II, Cr II, Cr III, Fe II, Fe III, Ni II, Ni III. Several other species are possibly present: B II, N II, O II, P III, C I, CI II, V II, Ga II, Ga III.

About 50% of the observed lines are identified to a single atomic transition. Other 30% of the lines could be attributed to blends of two or more components.

A tracing of the spectra and a complete list of the measured lines will be given elsewhere (Ref.12) both including the line identifications. An example of the identified spectra is displayed in Fig.1 for the limited range 147.0-148.8 nm.

4. CONCLUSION

By combining the IUE high-quality spectra of the normal B stars π Cet and ν Cap with an updated selection of the best laboratory line data, we intend to provide an identified atlas in the range 125-200 nm, where the line identification is an essential preliminary step to many further investigations based on the ultraviolet spectra of early-type stars.

5. REFERENCES

7. Kelly R L 1983 (updated line list on magnetic tape)
THE UV SILICON SPECTRA OF EARLY B STARS

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ABSTRACT

The UV silicon spectra of a sample of mid- to early B stars are examined and compared to models. It is found that some of these lines are extremely sensitive to stellar temperature and luminosity. Although the models fail to predict the quantitative behavior of the line strengths, they do, in most instances, describe their qualitative behavior.

1. INTRODUCTION

The UV spectra of early B stars contain a rich silicon spectrum. Walborn and Pasek (1984) have pointed out the strong luminosity dependence of the Si IV wind lines, but the photospheric lines of Si II and III have received very little attention. Kamp (1978, 82) analyzed some of these lines in a few stars near the main sequence, but he did not consider more luminous stars.

The purpose of this paper is to explore how strongly the equivalent widths of the photospheric Si II and III lines of early B stars vary and to determine how these variations are related to other, well studied, atmospheric diagnostics. Specifically, we are interested in how the lines are related to MK spectral types and effective temperatures and surface gravities derived from uvby-β photometry.

2. THE DATA

Table 1 lists the program stars and their relevant data. Figure 1 displays their positions on a [c, β] - [β] diagram. The program stars sample the temperature and luminosity range of early B stars as uniformly as possible and have relatively low rotational velocities in order to minimize line blending problems. Only B0.5 - B5 stars are analyzed since Si II lines are too weak in earlier B stars and Si III lines are severely blended with numerous metallic lines in later B stars. Because the 2 Si II lines measured are fine structure lines, it was also necessary to avoid stars situated in dense H II regions, since these environments can produce sizable interstellar contamination.

<table>
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<td>θ Cru</td>
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<tr>
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<td>B1 Iip</td>
<td>--</td>
<td>--</td>
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<tr>
<td>14765</td>
<td>θ Sco</td>
<td>B1 III</td>
<td>26,500</td>
<td>4.09</td>
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<tr>
<td>50707</td>
<td>15 Cma</td>
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<td>25,700</td>
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<td>51309</td>
<td>ο Cha</td>
<td>B3 II</td>
<td>17,230</td>
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<td>B3 IV</td>
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<td>65975</td>
<td>ι Car</td>
<td>B3 Ivp</td>
<td>16,720</td>
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<td>23556</td>
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<td>B3 V</td>
<td>16,740</td>
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<td>θ Her</td>
<td>B5 IV</td>
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<td>2.73</td>
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Table 2 lists the lines measured. Figure 2 compares these lines in a Bl V and a Bl Ib. The stars shown have nearly identical Si III λ1299 equivalent widths, but their other silicon lines differ noticeably in strength. For example, the Si III singlets at 1312.5 and 1417 Å are stronger in the supergiant, as is Si II λ1265. On the other hand, Si II λ1309 is stronger in the main sequence star. This example demonstrates the variability we might expect.

3. RESULTS

There are several interesting correlations in the data, but only a few can be shown. All of the line data are displayed in log(equivalent width (mA)).

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**TABLE 2 -- SI LINES MEASURED**

<table>
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<td>Si II</td>
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<tr>
<td>Si III</td>
<td>1294.54, 1296.73, 1298.89, 96, 1303.32 (triplets)</td>
</tr>
<tr>
<td></td>
<td>1312.59, 1417.47 (singlets)</td>
</tr>
</tbody>
</table>

---

Fig 1. Positions of the program stars on the [c1]-β plane. The symbols represent different luminosity classes as follows: filled circles IV, V; half filled circles III; belted circles II; open circles Ib, Iab; crosses Ia. The model grid is for Kurucz (1979) models using Kurucz's uvby calibration and Schmidt's (1979) β calibration. The models are labeled by log(g) along the top and 10^3*T along the side. Several supergiants have photometry which indicate surface gravities less than the minimum calculated by Kurucz. These stars cannot be assigned T_eff and log(g) values.

Fig 2. Normalized spectra of a Bl V and a Bl Ib. Stellar lines are indicated above the spectra and interstellar lines below.
Figure 3 shows how the Si III λ1299 triplet and the λ1417 singlet vary with spectral type. The λ1299 line attains a broad maximum between B2 and 3 and shows very little luminosity dependence, except for the later types. On the other hand, λ1417 depends much more strongly on luminosity than temperature throughout the entire region, indicating that it is a very sensitive luminosity diagnostic.

Figure 4 shows Si II λ1264 versus spectral type (Fig. 4a) and the balmer jump index [c,] (Fig. 4b). The luminosity dependence is not nearly as clear in 4a because Si II λ1265 is so temperature sensitive that the coarseness of the HK bins smears out the dependence. On the other hand, the [c,] index sorts out the luminosity dependence nicely.

Figure 5 shows the temperature dependence of Si II λ1265 and Si III λ1417. The models calculated by Kamp (1978) are also shown. Because these models are based upon a different model grid than the one used to derive the temperatures, exact agreement cannot be expected. Nevertheless, the fact that the predicted luminosity dependence of λ1265 for a fixed temperature is the opposite to that observed cannot be accounted for by the different models. However, the models do seem to account for the variation of λ1417 reasonably well, considering that log(g) = 3.0 corresponds to class II on average, and that there are no models for the supergiants.
Figure 6 shows how λ1417 depends on λ1265. This combination is less model dependent, and the Kamp models seem to follow the observed trend. A few stars seem to be in positions which are discordant with their luminosity classes. Whether this is due to differing Si abundances is being considered more closely.

4. CONCLUSIONS

Although the surface has barely been scratched, a few points can be made even at this early stage of the analysis.

1. Si III λ1417 is very luminosity sensitive in stars above the main sequence. This makes it an excellent complement to [c_i] - β which is most sensitive near the main sequence.

2. Si and 2 stars near the MS are especially interesting. Not only are both Si II and III lines strong, but Si IV is also photospheric. Therefore, these stars present the unique opportunity to examine 3 stages of ionization of an atom in the same atmosphere.

3. The agreement with available models isn't all that it could be. However, these calculations are based on older models for the atmospheric structure which are known to be inadequate (Erhorn et al. 1984).

Some avenues for further research include:

1. Analyzing the [c_i] - β and Si spectra more closely in stars with discordant Si line strengths in order to determine whether Si abundances variations are present.

2. Examining how the strength of the wind lines in the more luminous stars correspond to the photospheric lines. This could be very revealing, since the wind lines are far more sensitive to abundances (Walborn and Paren 1985, Massa et al. 1984) as well as rotation and magnetic fields (Poe and Friend 1986).

3. Analyzing the C II and III lines in the same stars in order to determine whether relative Si to C abundance variations can be found.

REFERENCES
C IV and Si IV in IUE Spectra of Normal B8-A0 Stars: UV Identified Be/Ae Stars?

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C.A. Grady
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IUE Observatory, Goddard Space Flight Center

ABSTRACT

We present the results of a survey of archival IUE high dispersion spectra of 42 B6-A2 stars within 200 pc. Five of the program stars showed significant C IV and Si IV absorption. All of the stars with detected C IV have $v \sin i \geq 190$ km s$^{-1}$. Sharp absorption cores were present in Si II in 3 of the objects, indicating that these are previously unrecognized shell stars. Three of the stars have variable or asymmetric C IV profiles which are consistent with the C IV and Si IV being produced in stellar winds. One star had C IV in the form of a shortward-shifted discrete absorption component, similar to those observed in Be stars. The data are compared with similar data for Be and B shell stars.

Keywords: Stellar Winds, Shell Stars, Interstellar Material

1. INTRODUCTION

Recent studies of nearby, apparently normal B8-A0 stars using IUE data have detected C IV and Si IV. The presence of these ions in the spectra of such cool stars has been interpreted as evidence for the presence of C IV and Si IV in the interstellar medium (ISM), since these stars are clearly too cool to photoionize the surrounding interstellar gas and produce these ions. Although measurable amounts of C IV and Si IV, arising in evaporative interfaces or cloud skins, should be observable over large path lengths, the presence of these ions over such short lines-of-sight could pose a significant problem for our current understanding of the physical processes occurring in the interstellar medium (ISM). Alternatively, if C IV and Si IV were to have a stellar origin, it would remove the need to provide an interstellar interpretation. Instead, we would be confronted with explaining how these ions can be present in spectra of stars with only $T_{\text{eff}} \approx 10,000 - 12,000$ K.

Yet, studies of Be and shell stars with spectral types from B9.5-B0.5 show that C IV and Si IV are common (Ref. 1, 4) and seem to be closely linked to stellar mass loss. The C IV features in the B6-B9.5c stars show shortward-shifted and often asymmetric absorption. Significant line profile variations are known in four of these stars. A further characteristic of the Be stellar winds is that C IV features are detected only in objects with $v \sin i \geq 150$ km s$^{-1}$. Slettebak and Carpenter (Ref. 5) in a preliminary study of stellar winds in both normal and emission line stars found evidence for C IV and Si IV in the normal stars at later spectral types than would be expected based on simple radiation-pressure driven stellar wind models. Their survey included only single observations of a few stars, precluding evaluation of the source of the highly ionized material.

2. PROGRAM STAR SELECTION CRITERIA

We have restricted our survey to B6 to A2 stars within approximately 200 pc. More distant stars were excluded, both because the lines of sight would have a larger probability of intersecting one or more evaporative interfaces or cloud skins, and because the stellar spectra would require longer exposure times, and hence have lower signal to noise. Our sample includes only stars in luminosity classes V-III, excluding more evolved objects which may retain highly ionized stellar winds as they evolve off the main sequence. We have further restricted the sample to stars with $V \leq 6$, excluding more evolved objects which may retain highly ionized stellar winds as they evolve off the main sequence. We have further restricted the sample to stars with $V \leq 6$, excluding more evolved objects which may retain highly ionized stellar winds as they evolve off the main sequence. We have further restricted the sample to stars with $V \leq 6$, excluding more evolved objects which may retain highly ionized stellar winds as they evolve off the main sequence.

Figure 1 shows the distribution of program stars in galactic longitude, latitude, and distance from the Sun.

3. LINE IDENTIFICATION AND ANALYSIS

Two factors limit our ability to detect weak absorption features in the IUE spectra. The first is the finite S/N ratio of the data. Typically, for well-exposed spectral regions a detection limit near 15 mÅ is implied for sharp interstellar-like features in optimally exposed O and early-type B star spectra. The C IV features in the B6-B9.5c stars show shortward-shifted and often asymmetric absorption. Significant line profile variations are known in four of these stars.
under the assumption that the absorption features are on the linear part of the curve of growth. The second, and typically the most important, factor limiting the detectability of weak absorption features is contamination of the region of interest by other lines. The UV spectra of HS-A2 stars are rich in lines due to singly ionized elements. Fe II lines are particularly prominent, especially in the vicinity of the C IV and Si IV absorption features, which are visible in both highly ionized species. Our criteria for identification of C IV and Si IV absorption in the spectra of these stars rests on the amount of absorption from these highly ionized species. Our criteria for identification of C IV and Si IV absorption in the spectra of these stars rests on the following criteria.

1. Sharp or strong absorption features must be visible at or near the rest wavelengths of the C IV and Si IV resonance doublet transitions. Practically, this corresponds to a requirement that the absorption feature have a depth which is more than 5 percent deeper than the envelope of noise and other weak spectral features in the vicinity.

2. The absorption features in both members of the resonance doublet, and preferably in both the C IV and Si IV doublets, must coincide in velocity. In this process we have utilized the reliable relative internal wavelength scale of the SWP camera. Previous studies over the wavelength range 1200-1500 Å have shown that radial velocity measurements of sharp photospheric or interstellar features internal to an IUE image are reproducible to ±2 km s⁻¹, while measurements of similar features from image to image suggest that one can achieve an accuracy of ±5 km s⁻¹ with optimally exposed data (Ref. 3).

3. Absorption from the lower f-value member of each doublet should not be stronger than that produced by the higher f-value line. In the case of C IV, Fe II absorption can contaminate the λ1550 line.

4. RESULTS

Five of the program stars showed definite C IV and Si IV absorption. An additional five stars may have some C IV and Si IV, but the absorption features are highly blended with adjacent absorption lines, predominantly those of Fe II, precluding reliable measurements. The remainder of this section will be devoted to the stars with firm detections.

HH 1147 (HD 23383, B9 Vnu, Ref. 6, v sin i = 440, Ref. 7). Absorption in C IV and Si IV was first reported in this star's spectrum by Molaro et al. (Ref. 1). In addition to C IV and Si IV absorption features which are visible in both members of the resonance doublet, a strong absorption core is present in the Si IA 1533.4 line at the same radial velocity as the highly ionized features.

ζ² Ori (HD 40729, A1 V, Ref. 6, v sin i = 245, Ref. 7). Strong (300 mA) C IV and Si IV absorption features are present in the IUE spectrum of this starscope of the spectroscopic binary. The IUE data do not indicate the presence of a sharp absorption core in Si IA 1533.4.

HH 2191 (HD 42477, A0 Vn, Ref. 6, v sin i = 250, Ref. 7). The IUE spectrum of this star shows strong C IV (W₄ = 270 mA) and Si IV features with minimal contamination by adjacent spectral lines. The radial velocities of the highly ionized features coincide with the radial velocities of the absorption cores of the two Si II lines. Both the higher oscillator strength C IV and Si IV profiles show blue asymmetric absorption at -135 and -111 km s⁻¹, respectively, suggesting that a stellar wind is present.

Z Cz (HD 119921, A0 V, Ref. 6, v sin i = 437 km s⁻¹, Ref. 6). The presence of strong C IV and Si IV absorption in the IUE spectra of this star was first reported by Freire Ferrero and Fedel (Ref. 2). They suggested that the C IV and Si IV were produced in the interstellar medium due to the comparatively late spectral type for this object. Despite the high v sin i, a sharp absorption core is present in Si IA 1533. Inspection of the 2 SWP spectra of this star reveals some line profile variability in both C IV and Si IV. In one spectrum, SWP 22668, the higher oscillator strength members of the resonance doublets show two discrete absorption components at -155 and -60 km s⁻¹. This spectrum also has the highest C IV edge velocity detected, -210 km s⁻¹. The other images only showed one absorption component, which is displaced shortward of the Si II absorption core by 50 km s⁻¹. The Si II absorption core is also variable with equivalent widths ranging from 49 to 160 mA.

The presence of variability in both the highly ionized and Si II features rules out an interstellar origin for the C IV and Si IV in this star. The presence of blue-asymmetric
**UV IDENTIFIED BE/AE STARS**

399

**3.5**

**2.5**

**2**

**1.5**

**1**

**0.5**

**0**

Figure 2: UV spectrum of 69 V stars. Each spectrum has been continuum normalized and offset for clarity of presentation. The top spectrum is a normal B star, HD 26793, showing no C IV or circumstellar Si II absorption. The circumstellar shell absorption is particularly well developed in the spectrum of HD 23383. **σ** Her (HD 119630) shows both strong Si II absorption and C IV.

**3.5**

**2.5**

**2**

**1.5**

**1**

**0.5**

**0**

Figure 3: UV and Si II at 69 V. The spectra have been normalized and offset as in Figure 2. The top spectrum of HD 21686 shows an A0 star without C IV absorption. HD 119921 shows especially strong C IV absorption.

The UV spectrum of this star is characterized by strong C IV (550 mA) and Si IV absorption. The C IV A1548 profile is blue asymmetric, with an edge velocity of -250 km s^{-1}, consistent with the existence of a strong stellar wind. Significant profile variability is observed from SWF 28830 to SWF 29108 when the C IV equivalent width increased by 200 mA. A sharp absorption core contributing 100 mA is present in Si II A1533. This object has a large Hα AS 12 micron excess.

5. INTERPRETATION

Four out of the five program stars showing C IV and Si IV in their UV spectra have significant line profile variations in those lines, blue-asymmetric absorption profiles, or significant absorption in Si II A1533.4. An interstellar origin for the C IV and Si IV can be immediately ruled out for the two program stars Z Cen, and **σ** Her which show line profile variability similar to that observed in Be stars. One star, HD 42177, has been observed too infrequently with the IUK to determine whether it also has variable C IV or Si IV. Interstellar absorption would be expected, especially over the short path lengths to these stars to comprise, at most, at IUK's resolution, one essentially Gaussian absorption feature. Absorption profiles which are asymmetric on the short-wavelength side of the profile, or variable absorption profiles are characteristic of stellar wind profiles. Thus, the available data for three of the program stars, suggest the production of C IV and Si IV in winds, rather than in the local interstellar medium.

Two of the stars with variable wind profiles also show Si II A1533.4 absorption, as does one other program star, HD 23383. The detection of a sharp absorption core in Si II in these high v sin i stars is particularly significant. The A 1533.4 line arises from a J level 287 cm^{-1} above the 0 Volt level which is responsible for the 1527.7 line, which typically has a strong interstellar contribution to the absorption. As a result of being an excited state line, the population of the 1533.4 line is highly density sensitive and is produced in the interstellar medium only in high density clouds. For the short path lengths to our program stars, and consequent low probability that the line of sight intersects a high-density cloud, any sharp absorption cores to the 1533.4 line are likely to be produced in the immediate circumstellar region rather than in intervening high density clouds.

The only program star without detected profile variability, asymmetric profiles, or evidence for a dense circumstellar shell is HD 30739. This star is noted as a spectroscopic binary, which could potentially account for the presence of highly ionized species.

The strength of the C IV absorption, line profile variations, distribution of C IV and Si IV absorption in radial velocity, and the presence of discrete components are similar to the C IV and Si IV profiles observed in the late-type Be stars (Ref. 4). Detection of a dense circumstellar shell via Si II A1533.4 absorption is also common among these stars, and is also seen in high v sin i A shell stars such as **σ** Pic. The available data are consistent with at least 80 percent of the program stars with C IV absorption being hitherto...
unrecognized Be or B and A shell stars.

The detection of previously unrecognized Be or A shell stars is not unexpected, since the optical surveys, upon which identification is usually based, identify only those stars currently showing either H\alpha emission, or particularly strong circumstellar shell absorption. Long-term monitoring of selected bright Be stars has shown that the optical spectrum can alternate, on timescales of months to years, between an essentially normal B spectrum, to one showing emission lines, or to a spectrum dominated by shell absorption features. In at least one case, UV signatures of mass loss, in the form of C IV absorption, have been observed to be present at a time when no emission was visible in H\alpha.

REFERENCES
ULTRAVIOLET PROPERTIES OF IRAS-SELECTED Be STARS

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ABSTRACT

We present preliminary results of a study of IRAS-selected Be stars using data from IUE. We have obtained new IUE observations of 35 Be stars from a list of stars which show excess infrared fluxes in the IRAS data. We find that IRAS-selected Be stars show larger C IV and Si IV equivalent widths than other Be stars. We also find that the excess C IV and Si IV absorption seems to be independent of spectral type for IRAS-selected Be stars later than spectral type B4. We interpret this as evidence for a possible second mechanism setting in conjunction with radiation pressure for producing the winds in Be stars. No clear correlation of IR excess or \( \sin i \) with C IV or Si IV equivalent widths is seen, although a threshold for the occurrence of excess C IV and Si IV absorption appears at a \( \sin i \) of about 150 \( \text{km s}^{-1} \). These results are preliminary, as this project is ongoing research, and more stars will be included as data become available.

Keywords: Be stars, ultraviolet spectra, infrared excesses, C IV equivalent widths

1. INTRODUCTION

Be stars have been the subject of intense study with IUE since its launch 10 years ago. Snow and Marlborough (Ref. 1) first pointed out the presence of asymmetric line profiles in the spectra of Be stars on the basis of ultraviolet data from the Copernicus satellite. Since then, a number of studies have been done with IUE to investigate the ultraviolet characteristics of Be stars (Ref. 2-5). Results of these studies indicate that strong, high velocity, highly ionized winds are a common characteristic of Be stars; variability and the presence of narrow components in the resonance lines of C IV are also important features.

Near-IR observations of Be stars have also been carried out by a number of observers. Gehrz, Hackwell, and Jones (Ref. 6) undertook a large survey of Be stars at near-IR wavelengths. They reported near-IR excesses for the Be stars in their sample, which they showed were due to free-free emission from the circumstellar material. They did not find evidence for a correlation of IR excess with \( \sin i \).

With the completion of the IRAS mission in 1983, far-IR data became available for the first time for a large number of Be stars. Coté and Waters (Ref. 7) analyzed the IRAS data and found that their Be stars showed significant IR excesses in at least one IRAS band. In other analyses of the IRAS data, Waters (Ref. 8) found no direct correlation of the 12 \( \mu \text{m} \) excess with either \( \sin i \) or spectral type, although some thresholds did seem to be present. He found that stars of early spectral type (B0-B4) showed larger excesses than stars of later spectral type (B5-B9). He also found that large 12 \( \mu \text{m} \) excesses only tended to occur in stars with \( \sin i \) larger than about 200 \( \text{km s}^{-1} \).

A number of ad hoc models have been proposed to try and explain various Be star characteristics. Good reviews of the current state of modeling can be found in Slettebak and Snow (Ref. 9). Many researchers now believe that the basic geometry of Be stars consists of an axisymmetric concentration of cool material in the equatorial region combined with hot, high velocity polar regions. A study using both infrared and ultraviolet data may provide some useful insights into the true nature of the Be phenomenon. Accordingly, we have begun a program to obtain IUE data (both archive and new observations) for Be stars which show infrared excesses in the IRAS data. In this paper, we present some preliminary results from the study, including only those new observations which we have obtained. The archive data will be included in the complete paper to be published elsewhere.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Selection criteria

For this study we have observed Be stars which showed infrared excesses in at least one of the IRAS bands. Hereafter these stars will be referred to as IRAS Be stars. We used the results of Coté and Waters (Ref. 7) to select these stars. From their list, we have chosen stars for which there are no (or in some cases only one or two) high dispersion IUE spectra available. We have attempted to obtain a good cross-section of spectral types and luminosity classes, although at this point in the study there remain some gaps, noticeably at very early spectral types (B0-B1). The archive data, combined with future observations, will remedy most of these deficiencies.

2.2. Observations and data extraction

The sample of new observations which we will discuss here consists of 35 Be stars. For each star, at least one high dispersion SWP spectrum was obtained with IUE. In some cases, more than one spectrum was obtained. Because we have found that a number of these stars show interesting characteristics at Mg II, we have also begun obtaining high dispersion LWP spectra of the stars as well, but at present only 13 of our sample stars have LWP spectra available.
3. RESULTS

3.1. C IV and Si IV

We have measured the equivalent widths of the C IV and Si IV line profiles in each of our spectra. Uncertainties in individual equivalent widths are estimated to be 0.3 to 0.5 Å, and are due to uncertainties in the placement of the continuum and of the point at which the absorption feature returns to the continuum. For those stars which have more than one observation, we have taken the mean value of all the observations as the equivalent width for purposes of this study. This approach minimizes the effects of variability.

When the C IV equivalent widths are plotted against those for Si IV, a reasonably good correlation is found (see Fig. 1). This is not an unexpected result, since both lines are formed in similar regions of the wind. However, it does show that the Si IV arises mostly in the wind, which is not obvious from the shapes of the line profiles alone in many cases. The result is a useful one, since it means that the correlations with other parameters will be similar for both C IV and Si IV. Although we have examined the data for both lines, we will present only the results for C IV from here on, since the results are the same in both cases.

3.1.1. Comparison with normal B and He stars. In order to compare the IRAS-selected He stars with normal B stars and with non-IRAS He stars, we have chosen to average together the equivalent widths of all stars in each spectral class. Averaging helps to minimize the effects of the well-known time variability in the ultraviolet spectra of He stars, thus producing a better indication of overall trends than would be seen in individual stars. By averaging, we have assumed that all stars of a given spectral type within each data set are similar. This is not completely correct, since obviously there are different luminosity classes as well as a range of other stellar parameters included within each type. Nevertheless, the stellar photospheric temperatures are approximately the same.

We have used the data from Grady, Bjorkman, and Snow (Ref. 5) and Kallrath et al. (Ref. 14) for our normal B star sample. We have taken the first results from these same papers and removed those stars which appear in the list of IRAS He stars to produce our non-IRAS He sample. There is therefore no overlap of stars between the three data sets.

We plot the mean equivalent widths vs. spectral type for all three data sets in Fig. 2. The error bars represent the standard deviations of the mean equivalent widths. This is a measure of the intrinsic variations within each spectral type. We will take the curve shown for the normal B stars to define a standard mean equivalent width for each spectral type. We will use this value to define an excess C IV equivalent width for He stars which will be discussed later. A similar process has been followed for the Si IV data.

The data show a definite difference in mean C IV equivalent widths for the three data sets. Be stars in general show a larger C IV equivalent width than do normal B stars. This agrees with the findings of Grady, et al. (Ref. 5, 14). In addition, it is clear that the IRAS Be stars show even larger C IV (and Si IV) equivalent widths than do the non-IRAS Be stars.

3.1.2. Dependence on spectral type. From Fig. 2, we notice that the equivalent width for the Be stars remains approximately constant later than spectral type B5. For spectral types earlier than B5, the equivalent widths increase with luminosity, as is expected for radiation driven winds; however, the excess mean equivalent widths, defined by $W_{ex} = W - W_{ave}$, are at most only a weak function of spectral type earlier than B5, and remain approximately constant later than B5.

3.1.3. Correlation with $v \sin i$. The excess C IV equivalent widths for the IRAS Be stars are plotted vs. $v \sin i$ in Fig. 3. Note that in this case the data points represent values for individual stars, and not mean values, since wide ranges of $v \sin i$ occur within each spectral type. There is no clear correlation of C IV excess equivalent width with $v \sin i$, although there does appear to be a threshold in $v \sin i$ (at around 150 km $s^{-1}$) at which excesses begin to occur. Above this $v \sin i$ value there is a wide range of excesses. One might think that this could be a selection effect due to the inclusion of only the IRAS Be stars, which have preferentially larger values of $v \sin i$. However, we have examined this more carefully by including the non-IRAS Be stars and the normal B stars, and we find that the threshold is not just a selection effect. It also occurs in the Si IV data. This result is interesting in light of thresholds found at similar $v \sin i$ values for the occurrence of IR excess (Waters, Ref. 8), and for the UV, polarization, and Hα (Grady, et al., Ref. 5).

3.1.4. Correlation with IR excess. Since the IRAS Be stars show noticeably higher C IV mean equivalent widths than the other stars, we might expect a possible correlation of C IV equivalent width with 12 μm excess. However, as we see in Fig. 4, this is not the case. The C IV equivalent widths do not correlate with the 12 μm excess defined by Coté and Waters (Ref. 7). The Si IV data also show no correlation.

3.2. Mg II

At this point in the study, our sample of stars with IUE spectra is limited. However, several interesting results are apparent from these spectra. Of the 13 stars for which Mg II profiles have been examined, 4 show evidence for emission wings and 1 star (HD 50123) shows prominent P Cygni profiles at Mg II (shown in Fig. 5). The remaining stars show only normal Mg II absorption. These results can be better examined as soon as we have completed our upcoming observations.

3.3. HD 50123

In addition to the P Cygni profiles at Mg II, HD 50123 shows several other interesting characteristics in the IUE data. It shows absorption features at N V (λλ 1238, 1242 Å), which is very unusual for a star of its spectral type (B 6 IV type). It also has strong lines of Si IV and C IV, as well as lower ionization lines of Si II and S II. It shows a remarkable range of ionization, as well as large time variability in the line strength. We are continuing to observe HD 50123. A paper detailing the results of these observations is in preparation.
4. INTERPRETATION

Although the data presented in this paper are preliminary, some interesting results are beginning to emerge. We consider some possible interpretations of these data in terms of models for Be stars. Since C IV and Si IV are superionized states in stars later than about B2 (or earlier for C IV), we assume that these lines are produced in the wind of the stars and are not photospheric. This is not new, and has been known about Be stars for some time. However, the fact that stars with large IRAS IR excesses also tend to exhibit excess C IV and Si IV equivalent widths suggests that there is an enhanced density in both the IR and UV producing regions of the circumstellar envelope. Perhaps this can be interpreted as evidence that the same underlying physical mechanism is responsible for enhancement in both regions.

Higher luminosity will result in larger mass loss rates if a radiatively driven wind is responsible for the mass loss. The results in Fig. 2 seem to bear this out for the normal B stars, but the excess C IV and Si IV mean equivalent widths seen most notably in the IRAS Be stars cannot be explained by radiation driven winds alone, since they do not appear to be luminosity dependent for later spectral types. One possible interpretation is that this is direct evidence of a second mechanism acting in conjunction with radiation pressure to produce the winds in Be stars. This same mechanism would also have to produce the IR excess, since the effect in the UV is seen most strongly in those stars with IR excesses.

The well-known link of Be stars to high values of \( \sin i \) shows that rotation must clearly play an important role. Observations using many wavelengths and techniques have shown thresholds at similar values of \( \sin i \) for the onset of different aspects of the Be phenomena, including polarization, IR excess, narrow components, He I characteristics, and now UV excess absorption at C IV and Si IV. These other observations also show no correlation with \( \sin i \) other than the threshold. One might interpret this as evidence for the onset of an instability which initiates the mechanism responsible for these effects.

From the result that the relationship between IR excesses and excess C IV equivalent widths is merely a threshold, rather than a direct correlation, we must conclude that the densities, and hence the mass loss rates, in the IR and UV producing regions may be different. What does this imply for models of Be stars?

In the spherically symmetric model of Dzian (Ref. 15), the UV and IR producing regions are assumed to lie at different radii in the wind. If this is the case, then the behavior of the superionized UV producing region and the cooler IR producing region must be linked, simply because of the requirement that mass be conserved as it flows out through the wind. Hence a change in one region would produce a change in the other region, perhaps offset slightly in time. The observations presented here do not support this requirement. One might argue that this is due to the lack of simultaneous observations in the IR and UV, but we do not believe this can necessarily explain the problem.

First, there is no clear evidence for large variability of Be stars in the IR. In fact, Gehrz, et al. (Ref. 6) find no evidence of variability in the near-IR over a timescale of about one year. The IRAS Point Source Catalog provides some information about the probability that its sources have varied over the lifetime of the IRAS mission (about one year). The IRAS Be stars in general do not show large probabilities of having varied. Second, if a large sample of stars is used, and multiple observations of individual stars are averaged together, then even the effects of UV variability, which are well established, can be eliminated by statistical means.

In the case of an axisymmetric model in which the IR producing region is assumed to be equatorially concentrated (not necessarily in a thin disk) and the UV producing region is assumed to exist at higher latitudes, one can perhaps explain the results of this study more easily. An axisymmetric geometry permits different mass loss rates in the UV and IR producing regions, since they are not radially linked. This geometryallows uncoordinated behaviour to occur in the two regions even if the underlying driving mechanism is the same for both regions. This picture is also consistent with polarization measurements, which provide strong evidence for non-spherical symmetry (Coyne and McLean, Ref. 16).

More recently, evidence has been presented for non-radial pulsations (NRP) in Be stars. Baade (Ref. 17) provides a good overview of this evidence. The properties of NRP are such that they fit rather nicely with the axisymmetric model, as well as with the idea of instabilities and underlying temperature independent driving mechanisms for the Be phenomena. NRP might also explain much of the scatter observed in the data, since different modes might well occur in different stars, changing the relative mass loss rates in the polar and equatorial regions from star to star. All of these ideas are of course speculative, and much work remains to be done before Be stars are well understood.

5. FUTURE PLANS

We have observations scheduled for this study in the coming year, and additional stars will be added to the results as the data become available. We will also include the appropriate IUE archive data. The complete results will be published elsewhere.

We wish to thank J. Bjorkman and R. Bars for several useful discussions regarding this project. T. Armitage and J. Ferguson provided invaluable help at the Colorado IUE RDAP. This work is supported by NASA grant NSG-5300 to the University of Colorado. The data were reduced at the IUE Regional Data Analysis Facility at the University of Colorado, which is supported by NASA contract NAS5-28731.

6. REFERENCES


Figure 1. C IV equivalent widths vs. Si IV equivalent widths for IRAS Be stars

Figure 2. C IV mean equivalent widths vs. spectral type

Figure 3. Excess C IV equivalent widths vs. $v \sin i$ for IRAS Be stars

Figure 4. C IV mean equivalent widths vs. 12 µm excess for IRAS Be stars (broken out by spectral type)

Figure 5. Representative Mg II profiles seen in HD 50123
AU II IN IUE SPECTRA OF CHEMICALLY PECULIAR STARS

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ABSTRACT

Heavy elements like platinum (Z = 78), mercury (Z = 80) and bismuth (Z = 83) have been detected in IUE spectra of chemically peculiar stars within the last few years. From our recent work on HR 465, we report the additional identification of the odd-Z element gold (Z = 79) in the spectra of some magnetic (CP2) as well as non-magnetic (CP3) stars. The importance of quantitative abundance analyses of the Pt-Au-Hg elemental sequence is pointed out, as well as a closer relationship between CP2 and CP3 stars as it may generally be assumed.

Keywords: Heavy Elements - Chemically Peculiar Stars

1. INTRODUCTION

The spectra of chemically peculiar stars of the upper main sequence (CP stars) are well known for their richness of spectral absorption lines. They present a number of elements which are generally hard or even impossible to observe in the spectra of other stars, with the possible exception of the sun. Beyond the iron-peak elements there are essentially three groups of sequences of observable elements, namely the peak around Sr-Y-Zr, the rare-earths and some heavy elements like platinum and mercury. The reason why these spectra are found in abnormal strength is thought to be due to diffusive separation of elements, depending on their atomic properties. However, to make the diffusion mechanism operative one needs a quiet atmosphere. The magnetic fields measured in CP stars, as well as a general slow rotation of most of the CP stars are in favour of this requirement. Nuclear processes have also been discussed extensively in the past and an observable odd-even abundance pattern of the elements according to the Harkins rule may be indicative of such mechanisms. On the other hand we observe obvious violations of this rule in some instances, especially in the case of the odd-Z gallium (Z = 31): IUE spectra of Ca II and Ca III lines have shown the enormous overabundance of this element in a lot of spectra of CP stars (Ref. 1-2).

In what follows we will discuss the identification of some heavy elements in CP2 and CP3 (Hg-Mn) stars, especially the case of Au II, the ion placed between the even-Z neighbours platinum and mercury.

2. THE OBSERVATIONS

The present study is entirely based on de-archived high resolution IUE spectra. Table 1 lists the stars and IUE image numbers. The spectrum of HR 465 is merged from six IUE images and the wavelength scale is shifted according to identified Fe II lines. It is used as a 'wavelength normal' and all other spectra are shifted with respect to this scale. No efforts are made to obtain absolute fluxes, but the spectra are normalized to a common scale for comparison purposes. 'Bad pixels', as indicated by the IUE Data Quality Values, are omitted in the figures.

Table 1

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</table>

3. THE IDENTIFICATION OF AU II AND OTHER HEAVY ELEMENTS

During the last decades, a lot of work has been carried out on heavy elements (beyond the rare-earths, i.e. Z > 71) that are detectable in chemically peculiar stars. Bidelman's (Ref. 3) identification of mercury in 1962, as well as the discovery of platinum lines by Dworetsky (Ref. 4), were important observational results in this respect. In some cases Pt and Hg were found to be enhanced up to ~5 dex over the solar system abundances. Yet the identifications were made on rather subordinate lines and, in the case of Au II, essentially dependent on a single line at A3984.
To confirm these results which are derived from optical spectra, spectroscopists had to await the launch of the IUE satellite, which enabled the direct access to the VUV region, where the resonance lines of these spectra are situated. In 1984 the identification of Pt II lines was reported by Dworetsky et al. (Ref. 5) leading to overabundances of about 4-5 dex. Similar results were obtained by Leckrone (Ref. 6, and references therein) for the second spectrum of mercury in Hg-Mn stars.

As far as the presence of Au lines is concerned, the situation has always been more complicated since observable transitions are even somewhat weaker as is the case with lines of platinum and mercury. There exist only few investigations reporting the possible identification of gold (e.g. Ref. 7-10), we note especially the thesis of M. Dworetsky (1971, Ref. 11). Concerning the three Au II lines at \( \lambda \) 336.0, 4016.10 and 4052.50 in the spectra of HR 4072 and \( \chi \) Lup he wrote therein: “The identification, while not completely certain, appears to be correct.”. The first definite identification of gold is, to our knowledge - to be found in an observatory report of Altman and Cowley (Ref. 12) in 1979. According to these authors there are at least 10 lines of Au I and Au II in the optical spectra of the mercury-platinum star HR 7775 and a preliminary crude estimate indicates that the abundance of gold is about five orders of magnitude above that in the sun. The equivalent widths of the Au II lines at 4016.10 and 4052.50 A are 11 and 14 mA respectively (Ref. 13). In 1978, Leckrone and Beeby (Ref. 14) mention a number of wavelength coincidences between observed features in the IUE spectra of the CP3 star \( \kappa \) CrB and Au III lines. Subsequent observations however failed to confirm these results (cf. Ref. 15, 16).

In an extensive line identification study, starting in 1985, we investigated the IUE spectra of the magnetic CP star HR 465. The systematic search included all elements within an ionization potential of less than 25 eV, i.e. roughly the first three spectra. With respect to the huge number of observable Fe II lines, the identification work was supported by a number of slow rotating comparison stars. In most cases the lines of Pt II and Hg II were found to be abnormally strong in the OP stars, while absent in 'normal' stars (Fig. 1 and Fig. 2). Special interest was devoted to the CP3 star HR 7775: apart from strong lines of Pt II and Hg II, this star is also well known for its bismuth abundance anomaly (+6 dex) detected in IUE spectra by Jacobs and Dworetsky in 1982 (Ref. 17).
Since most of the strongest lines of Au II are — just like Pt II, Hg II and Bi II — situated in the SWP region, we have looked for transitions of this ion. However, similar to the optical spectra, the situation is not as straightforward compared to the identification of Pt II and Hg II. Dependent on excitation energy restrictions, one has to concentrate on the multiplets UV 1 - UV 3. Unfortunately, a lot of these lines are masked by Fe II or situated in noisy echelle orders. But in spite of these shortcomings, there are at least a few lines that we consider to be a clue for the presence of Au II.

The most convincing results are obtainable with the raie ultime $\lambda$1740.516. Figure 3 shows the IUE spectra near this line, the wavelength is marked with a vertical line. Near $\lambda$1740.3 there is a relatively small feature in the tracings of the 'normal' stars Vega and $\nu$ Cap. The CP stars on the other hand reveal a more or less broad absorption that belongs to at least two lines. The 'bluering' contributor is due to an unclassified (Ref. 1) Fe II line at $\lambda$1740.312 and hence also present on Vega and $\nu$ Cap. Around $\sim$1740.5 we get the strongest absorption for HR 7775 and the same holds true for another Au II line at $\lambda$1600.58 (Fig. 4). Other promising features are the 0.0 eV Au II resonance line $\lambda$1362.330 and $\lambda$2000.81. We also find an absorption at the position of the Au II line $\lambda$2082.69, but this result deserves a careful treatment since this line is placed in a noisy LWR-echelle order.

4. VARIATIONS OF HEAVY ELEMENTS ON $\alpha^2$CVn

The CP2 stars are well known to show spectral, light and magnetic variations. These can be explained in terms of the oblique rotator model and usually occur in time scales of a few days (e.g. $\alpha^2$CVn: 5546939).

It is a remarkable fact that the spectrum of the well known magnetic CP star $\alpha^2$CVn shows lines of mercury and platinum as do the non-magnetic CP3 stars. Therefore, it is not surprising that one gets also convincing evidence for the presence of Au II in this star. However, we see that there are additional changes in the line strengths of the heavy elements, as indicated in Fig. 5-7. The phase (Eu II maximum: $\phi=0.0$) is given on the right side. While one may not consider the variation of the Hg II line $\lambda$1942.275 to be very significant, this is the case with Pt II at 1777.086 Å and is also obvious for Au II $\lambda$1740.516.
5. RESULTS AND DISCUSSION

The presence of Au II lines is interesting for at least two reasons. First we mention that quantitative abundance analyses of the Pt-Au-Hg sequence may be indicative of the involved mechanisms and discriminate between nuclear and non-nuclear abundance patterns. Contrary to platinum and mercury, the element Au has only one stable isotope, $_{197}$Au. Since this one lies on the main chain of the s-process, one may expect gold nuclei in evolved stars, even if no r-process occurred. It has been stated by Kuchneric (Ref. 10) that in this case the gold to platinum abundance ratio cannot exceed a value of 0.01. In the other extreme situation (i.e. only r-processing) the final abundance ratio should be of the order Pt/Au < 4. It is thus important to know whether the determined Au/Pt ratios lie nearer to 0.01 or 0.25, or even exceed this upper limit.

The high resolution spectrograph on board the HST may provide the necessary accuracy to answer this question in the near future with sufficient reliability.

The second point to emphasize is the presence of common features of heavy elements on magnetic (CP2) and non-magnetic (CP1) stars. We already mentioned the bismuth abundance anomaly on HR 7770. In agreement with a recent work by Cowley (Ref. 20) we confirm the identification of Bi II on HR 465. Similar to o CVn, this star exhibits a number of features that are typical for both CP2 and CP3 stars. In accordance with Cowley we note that there may be a stronger chemical link between these two classes of objects than it is generally assumed.

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Acknowledgement: I wish to thank C. Bendlin, C. Kirst and H. Schneider for valuable comments on an earlier draft of this paper.

Fig. 5-7 
Variations in the strong lines of Pt II, Au II and Hg II on o CVn

$\phi = 0.33$

$\phi = 0.52$

$\phi = 0.79$

$\phi = 0.89$

$\phi = 0.97$

$\phi = 0.99$

$\phi = 0.90$

$\phi = 0.11$
VALIDITY OF THE CLASSIFICATION OF UV CALIBRATED STARS

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ABSTRACT

The investigation of the validity of the UV calibration of stars in the range of UV and Lyman spectral regions, which is based on the IUE and HST observations, is presented in this paper. The UV calibration of the stars is based on the comparison of their UV spectra with the model spectra.

In the next section, the UV calibration of stars is discussed. The UV calibration of stars with different UV parameters is compared with the model spectra.

In the last section, the results of the UV calibration of stars are presented and discussed.
Figure 1. The H I observed PDR spectra of NGC 7538 and that of 41 Tau in the vicinity of 63 Ni AlIII lines. The dotted portions of the spectra are affected by resonance wings. Long horizontal lines denote estimated continuum levels.
CLASSIFICATION OF UV GALLIUM STARS

Table 1.

<table>
<thead>
<tr>
<th>SWP</th>
<th>Obs. Date (UT)</th>
<th>Exposure (min)</th>
<th>Phase</th>
<th>d_(414) (1414)</th>
<th>d_(414) (1495)</th>
</tr>
</thead>
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<tr>
<td>3863</td>
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<td>5.02</td>
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<td>0.11</td>
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<td>0.16</td>
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<td>1979 10.4526</td>
<td>5.02</td>
<td>0.688</td>
<td>0.31</td>
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</tr>
<tr>
<td>3866</td>
<td>1979 10.4944</td>
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<td>0.760</td>
<td>0.47</td>
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</tr>
<tr>
<td>3867</td>
<td>1979 10.5375</td>
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<td>0.852</td>
<td>0.45</td>
<td>0.31</td>
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<td>3868</td>
<td>1979 10.5804</td>
<td>3.67</td>
<td>0.934</td>
<td>0.51</td>
<td>0.28</td>
</tr>
<tr>
<td>3869</td>
<td>1979 10.6217</td>
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<td>0.013</td>
<td>0.56</td>
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</tr>
<tr>
<td>3870</td>
<td>1979 10.6624</td>
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<td>0.164</td>
<td>0.54</td>
<td>0.31</td>
</tr>
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<td>3871</td>
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<td>0.244</td>
<td>0.58</td>
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<tr>
<td>3872</td>
<td>1979 10.7444</td>
<td>3.67</td>
<td>0.322</td>
<td>0.15</td>
<td>0.24</td>
</tr>
<tr>
<td>3873</td>
<td>1979 10.7844</td>
<td>3.67</td>
<td>0.398</td>
<td>0.11</td>
<td>0.29</td>
</tr>
</tbody>
</table>

: Uncertain values.

4. DISCUSSION

We briefly discuss the results obtained above from the viewpoint of examining the validity of the spectral classification based on low-dispersion UV spectra. Jaschek and Jaschek (Ref. 1) estimated the Ga II line intensity in HD 124224 to be 3. This value suggests that HD 124224 may show the fairly strong Ga II line such as observed in stars listed in Table 2. However, we fail to find such a strong line on our high-dispersion spectra even if taking account of the large rotational velocity, as seen from the result (1) in section 3.1. A reconciliation in estimation of Ga II line intensity between low- and high-dispersion spectra might occur if the Ga II line was confirmed to be variable with its intensity stronger than that observed in our present high-dispersion data. Such confirmation of variability will need a large number of high-dispersion spectra which covers the phases as continuously as possible.

Finally, we make a concluding remark about the classification using low-dispersion spectra. Although the use of low-dispersion spectra is very effective in classification, high-dispersion spectra should be also utilized in so far as they are obtained with the UKA. A cross-check by high-dispersion spectra makes the classification more confirmed.

We would like to thank the World Data Center A for Rockets and Satellites for providing us with many released data. Data analyses were carried out at the Computer Center, University of Tokyo. One of us (M. T.-H.) would like to express his gratitude for a grant and a leave of absence from Tohoku University General Research Organization which made his visit to Dominion Astrophysical Observatory possible, and also for grants from Itoh Science Foundation and from The Japan Cultural Institute.

REFERENCES


Note: (1) The Ga II and Ga III lines are definitely present in these six stars with the large value of d_τ as an indicator of line strength. There exists an excellent agreement between the Ga II line intensity estimated by Jaschek and Jaschek (Ref. 1) and the values of d_(414), except for a small discrepancy in a case of HD 79491.
4. Takada-Hidai & K. Sadakane

5. Takada-Hidai & K. Sadakane

6. Takada-Hidai & K. Sadakane

References:


DETECTED UV VARIABILITY IN THE IUE SPECTRA OF
THE Ap-Si STAR HD 25823

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ABSTRACT

Spectral UV variabilities for the Ap-Si star HD 25823 are detected from five SW1'K images we obtained during a week in 1987. This particular and magnetic star presents also an uncommon overabundance of gallium. From the observations, it seems that silicon and gallium (and others also) abundances vary according to the rotational period of the star, as well as the magnetic field does. The anticorrelation observed between periodical variations of silicon and gallium confirms the predictions of the diffusion theory.

Keywords : Ap-Si stars ; Silicon ; Gallium ; abundance determination ; variable spectra ; high resolution IUE spectra

1. INTRODUCTION

Spectral line variations in Ap stars have been interpreted as produced by localized overabundances of the corresponding ions in the stellar atmosphere, like spots of different ionic concentrations, a phenomenon explained by the diffusion theory in the presence of magnetic fields (Ref. 1,2,3).

Radiative diffusion is modified by horizontal magnetic fields; theoretical computations show that silicon can concentrate in the presence of an horizontal magnetic field (Ref. 4) which in turn, prevents gallium accumulation (Ref. 5).

To test these theoretical results we observe with IUE the magnetic Ap-Si star HD 25823 (Si Iau, Ap7p Si I) which shows an overabundance of Si I (x1) and Ga (x200) (Ref. 7,8). This star has a slightly photometric variation in the visible and the deduced magnetic field varies also in a synchronous way according to the rotational period (Ref. 9).

We expected that the variation of magnetic flux values lead to variations in observed overabundance of Si I and Ga. A suitable spectral range to observe the resonance lines of Si II and Ga II and III is the SW1'K UV region.

2. THE OBSERVATIONS

We observed HD 25823 five times during one period in March 1987. The SW1'K images at high resolution were recorded with the large aperture and exposure times of 16 min 40 s.

This star is a spectroscopic binary, having synchronous rotation and revolution (Ref. 9). The phases $\phi$ were computed using (Ref. 10):

$$T = 2421944.74 + \text{P.E. (Julian days)}$$

$$\text{P} = 7.227424 \text{ days} = \text{period}$$

$$\frac{\text{phase}}{\text{period}} = \frac{\text{fractional part of } \phi}{\text{phase}}$$

The five spectra have phases $\phi = 0.143 ; 0.282 ; 0.345 ; 0.766 ; 0.863$.

These UV spectra (Ref. 11) show typical features of B stars, but with enhanced Si II and a small depression at 1600 A due to Si II autoionisation (Ref.12) and several intense Ga II and Ga III lines : at 1414.4 and 1495.1 the resonance Ga II lines, and at 1534.5 A the resonance line of Ga III in the wing of the Si II resonance line at 1533.4 A.

A rough comparison of the 5 spectra show spectral flux variations over the period, but in different ways, depending on the wavelength range.

We present some results concerning the variation of integrated fluxes. A more complete study will be published elsewhere (Ref. 13).

3. RESULTS

We compute mean fluxes in well defined intervals having a spectral line of interest ($\Delta \lambda \simeq \lambda$) or concerning more global or continuous characteristics ($\Delta \lambda \simeq 50 \lambda$) for each spectrum.

Table 1 displays some of the $\lambda$ intervals we considered, the relative variation of the mean fluxes between them, and the estimated phases of the minimum of these fluxes in the considered period.

The variations are illustrated on Fig. 1 for some mean fluxes.

From the data displayed, we point out that variations are real even if the relative variations are weak. This is supported by the fact that global relative variation for SW1'K images is of the order of 2% value in agreement with the observed photometric variations in the visible (Ref. 10 : $\Delta m = 0.02$ to 0.05 that is 2 to 5%) and also with the phases of minimum and maximum fluxes.

Actually, the relative variations we obtained are greater than 2% rising to 13 and 16.6% for the range 1250-1310 and 1334-1336 Å (Table 1).

Another argument is that different Δλ intervals belonging to the same ions vary in the same way, for example:

- the 3 intervals containing Ca II or Ca III (1410-1420; 1490-1500; 1520 - 1540) even if the contribution of Si II or III would have modified them. Their minimum and maximum occur at phases 0.6-0.65 and 0.1-0.3 respectively.
- the intervals containing Si II lines or the 1400 depression, in particular the intervals 1250 and 1360-1440 (see also Fig. 1). Their minimum and maximum are situated at phases 0.8-0.05 and 0.35-0.5 respectively.

To bring out properly the Ga variation, we considered also, the ratio R between the integrated fluxes at 1410-1420 and 1360-1440, assuming that in both of them the influence of the silicon is the same (Fig. 2 and Table 1).

4. DISCUSSION

The consideration of mean fluxes to analyse flux variations avoid us to define arbitrary continua, which could introduce some uncertainties in the results. From the data on Table 1 and Fig. 1 we can point out that:

- the integrated flux over 1200-1900 Å varies in a similar way as the visible one (Ref. 9);
- variations as large as 5 to 16% are displayed by the different intervals considered;
- the variations corresponding to intervals where Si or Ga are prominent features show quasi-sinusoidal curves in nearly antiphase.

Now, if we compare the variations of the magnetic field (Ref. 9) and that of the ratio R (section 3) (Fig. 2) we can deduce that the maximum of Ca II lines absorption corresponds to the maximum effective magnetic field. Similar results can be obtained with the intervals corresponding to Ga features.

Due to the fact that integrated fluxes for Si features are in antiphase with those of Ga, we obtain an agreement with theoretical results (section 1).

A schematic explanation of the observations is the following: when effective magnetic field is maximum (ϕ = 0.5-0.6) we observe mainly radial field (a polar region); horizontal fields are less important, silicon absorption also (Ref. 4) but gallium absorption can develop (Ref. 5). The contrary occurs when effective magnetic field is minimum (ϕ = 0.0-0.1) (Ref. 4, 9).

5. REFERENCES


Acknowledgements: We thank Dr. J. Herzenberger for the help in computer assistance and the use of VAX facilities at Meudon Observatory.
TABLE 1

<table>
<thead>
<tr>
<th>λ interval</th>
<th>Δλ (A)</th>
<th>relative variation (2) (1)</th>
<th>remarks</th>
<th>phases observed minimum</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 - 1900</td>
<td>700</td>
<td>2</td>
<td></td>
<td>0.15</td>
<td>0.55</td>
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<tr>
<td>1200 - 1300</td>
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<td>12.7</td>
<td>Si II (2)</td>
<td>0.80</td>
<td>0.40</td>
</tr>
<tr>
<td>1250 - 1310</td>
<td>60</td>
<td>13.1</td>
<td>Si II (2) (3)</td>
<td>0.85</td>
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</tr>
<tr>
<td>1300 - 1500</td>
<td>200</td>
<td>3.7</td>
<td>(4)</td>
<td>0.95</td>
<td>0.40</td>
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<tr>
<td>1360 - 1440</td>
<td>80</td>
<td>4.5</td>
<td>(4)</td>
<td>0.05</td>
<td>0.45</td>
</tr>
<tr>
<td>1500 - 1900</td>
<td>400</td>
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<td></td>
<td>0.40</td>
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</tr>
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</tr>
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<td>4.8</td>
<td>Ga II (2) + Si III line</td>
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<td>1523 - 1529</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1520 - 1540</td>
<td>20</td>
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<td>0.10</td>
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<tr>
<td>1665 - 1675</td>
<td>10</td>
<td>5.3</td>
<td>Al III (2)</td>
<td>0.25</td>
<td>0.65</td>
</tr>
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</table>

R = \frac{\text{Flux (1410-1420)}}{\text{Flux (1360-1440)}}

- 31.5

0.67 | 0.00

(1) the relative variation is defined as $1 - \left( \frac{\text{minimum value}}{\text{greatest value}} \right)$.
(2) resonance transition.
(3) photoionisation absorption of Si II.
(4) the 1400 A depression due to an autoionisation resonance of Si II.

Fig. 1 - Variation of the integrated (mean) fluxes over different λ-intervals as indicated by the arrows for each curve, over the phase φ.
The Galactic and LMC Extreme Emission Line Supergiants Compared: 

**IUE** Observations of the Henize - Carlson and Zwo Star Samples of Massive Supergiants

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8. Guest Observer, Kitt Peak National Observatory

**ABSTRACT**

We report on the second epoch of a study of the Henize - Carlson sample of galactic massive supergiants, and a comparison between the Galactic and LMC samples. Several of the stars, notably He3-335 and S 127/LMC, have very similar shell characteristics. There appears to be little difference, other than luminosity, between the LMC and Galactic samples. One star, He3-1492, has been detected with the VLA at 6 cm. The UV data is combined with IRAS and optical information.

**1. Introduction**

The extreme early-type emission line supergiants of the Magellanic Clouds (ref. 1), likely among the most massive stars in the Local Group, have previously been studied as part of an extensive project with IUE during 1981-1983 (Ref. 2) and subsequently have been discussed by several investigators (see e.g. ref.3). The galactic analogs of these stars, the Carlson - Henize sample (ref. 4) have been discussed (ref. 5) as part of a first survey of these stars in 1985-1986. The purpose of this note is twofold. One is to present the entire galactic sample from program 0DHSS. The second is to discuss these stars in the LMC which are most similar in morphology to the UV and optical spectra of the Galactic sample.

After nearly a decade of observing these stars with IUE, it is clear that many of the massive supergiants are spectroscopic, as well as photometric, variables. Several appear to be members of long - period binary systems (like R66). Some, like S18/SMC, may be the primaries in such systems, with a compact companion illuminating the stellar wind from which its power is derived by accretion. However, in other cases, like S127/LMC or S128/LMC = R127, there is reason to believe that much of the phenomenology observed in both the optical and UV is the result of an intrinsic envelope instability driving time - variable mass loss.

The optical properties of many of these stars, such as photometric and spectroscopic variability, are only poorly known. In most cases, they have been observed only photographically and at low dispersion. The original emission line object survey (ref. 7) was studied at slightly higher dispersion by Carlson and Henize (ref. 3). For most of those stars which Henize had flagged as Bep or P Cyg-like, in most cases, the emission lines dominate the optical spectra and there is little evidence for photospheric absorption, other than on P Cyg lines. The UV is the best diagnostic wavelength region for the study of dense shells in these stars, and the best indication of the extreme mass loss state in which most of these stars find themselves. There is no emission, in general, in the IUE spectra; rather, there are strong absorption lines which indicate that a pseudo-photosphere has formed (ref. 8) and that the spectral characteristics may be useful in determining mass loss rates.

We have previously employed the method of ultraviolet spectral types (UVST) to determine bolometric corrections, luminosities, and effective temperatures for the Magellanic Cloud stars. These have compared favorably with more detailed analyses of a few stars (ref. 9) and can be obtained without assumptions about the reddening. For the LMC and SMC stars, this is not so serious a difficulty; for the galactic stars, it is a stumbling block of considerable magnitude. The problem is that the intrinsic properties of these stars are not well known; they are in the galactic plane and consequently heavily reddened, and at large but unknown distances. Consequently, most of the clues employed in determining reddening corrections to the UV continua are lacking.

The UVST method has been tried for several of the
stars in program OBISS in order to test its effectiveness. For the massive stars, we have calibrated two indices for Si IV λ1400, the at (1400) and bI (1400) (Shore and Brown 1987, ref. 9) for the IUE standard star sample of B2V-1b and B3I In stars. These show that the UVST can be fit quantitatively as well as by the overall appearance of the continuum. In addition, we have calibrating, using the LMC/SMC sample and galactic stars, a set of line indices for Al III, Si III, C IV, N V, and Fe II/III features. These will be reported on elsewhere (Shore et al. preprint).

The application of the UVST method to the Magellanic Cloud supergiants makes it possible to determine the presence of dust from the strength of the 2200 Å feature. In the LMC, for example, this feature is weaker than in galactic stars. A sub-group of the “Zoo” stars shows strong absorption in this feature, especially S134/LMC and S30/LMC. Several of these have been found to contain dust (using near IR measurements). This will be useful as a test of whether the dust absorption in the stellar envelope or environment in the LMC is variable with time.

2. The Henize - Carlson Sample of Galactic Supergiants

The optical descriptions by Carlson and Henize (1979) suggest that the following sample of stars will be close matches for the Magellanic Cloud supergiants, having absolute magnitudes far in excess of what is normally observed for evolved stars. In fact, in the one high dispersion optical spectroscopic follow-up to date, we (Shore et al. 1988, preprint) have found that He3 - 1482 is a mass losing star more extreme than P Cygni. It is also known to be surrounded by an emission nebula in the radio, which appears resolved at 6 cm with the VLA A-configuration.

He3-407: This star was observed in 1985 and 1986 during OBISS. It displays only complex absorption in the SWP, with the LWP showing Mg II emission. This latter feature is unique among the sample stars, and a feature that may be variable. It will be important to re-observe this star, both to look for spectral changes in the absorption and in the P Cyg lines at Mg II, which we will be doing during 1988. The SWP spectrum is like R00 = S00/SMC.

He3-365: This star is most like S22/LMC, a strong Fe II/III band star. There are no emission lines observed in the SWP camera, and archival spectra show that the shell is stable on timescales of several years. It has, however, a large optical photometric amplitude (AV = 0.5") like S00/LMC = S Dor. It would be most interesting to observe this star several times, since several of the large amplitude variables appear to be binaries (Hutchings et al. 1987, ref. 3; Zickgraf, et al. 1985, ref. 11). We will be obtaining spectra in this (114°) round of IUE. The present sample of spectra serve to show that the variation is primarily in the Fe II “bands”, but there is no known contemporaneous photometry of this star. The UVST is B3-4 (S Dor-like).

The IRAS LRS spectrum shows a very strong 12μ emission feature, accounting for the 12μ excess in the star, and a nearly flat IR continuum. It is likely that the shell of this star is dusty, perhaps as dusty as S 30/LMC.

He3-395: This star is the most variable star in the Galactic sample, based on its optical properties, but we have to date only one IUE spectrum. Carlson and Henize give this star spectral type B2p while the UVST is B0-1; the Fe features near Al II 1850 are among the most interesting features in the spectrum. It is strikingly similar to S127/LMC = R126. Zickgraf et al. (ref 10) have discussed this star extensively, in the context of what it illustrates about stellar mass loss properties among the supergiants. They argue that S127 is a very rapid rotator, and that the origin of the extreme stellar wind is that the star is virtually at the stability limit for an object of low surface gravity. The facts that, as can be seen from the comparison of the SWP images of He3-395 and S127/LMC, these two stars are very similar argues that the more detailed study of these two will be most important in determining whether the model presented for the LMC star is applicable to the one in the galaxy. The two stars are so close in spectrum morphology that either there are two rotationally unstable hypergiants in the Local Group or some other process is at work. An interesting point is that S127/LMC is not known to be a large amplitude photometric variable. In IRAS data, only 12μ is detected and this is quite weak.

He3-407: This star has been observed several times with IUE (see fig. 2) and shows some evidence of long-term spectrum variations. The star is moderately bright, and one for which we have a long enough database to be able to say, with another year of observation, whether the trend toward stronger absorption lines is continuing. Similar behavior has been noted for S128/LMC. The UVST is B4-5 and the spectrum is a good match for S 73/LMC. IRAS data shows the envelope is likely warm dust; there is no evidence for a companion.

He3-759: To date, the only IUE spectrum we have of this star is far too weak to be useful for anything except ruling out strong emission lines. It is a class A star, having strong He II and He I emission in the optical, and one which appears similar to S9/LMC and S131/LMC and S30/LMC = R99. However, the latter two stars show strong emission in the UV, while we presently cannot say much about He3-759. The star was not seen by IRAS.

He3-1198: To date, the only IUE spectrum we have of this star is far too weak to be useful for anything except ruling out strong emission lines. This star is similar, both optically and in the IR, to S134/LMC = HD 38489 (ref 12). HD 38489 shows strong P Cygni profiles on the C IV and possibly N V lines, and strong C III [and Si III] emission. There is a possibility of P Cygni emission at C IV 1550 in SWP 28313, the only exposure we have for this star, but the S/N is very poor and the conclusions drawn from this spectrum are not trustworthy. IRAS data displays no strong evidence for a dusty or strong shell, since the IR excess is weak. It may be consistent with a strong stellar wind.
Hc3-1306: Strong absorption is observed at C IV 1549, Si IV is sharp and Al III is absent. The UVST is likely around 09-10h. The IR excess of the star is small, but the IRAS fluxes are poorly determined. There is a faint nebulosity associated with this star that may be contaminating the IRAS bands.

Hc3-1330: This star appears quite similar to S12/LMC = HDE 268582$, having a UVST of B2. The Si IV lines are well resolved, and there is also strong absorption at C IV. There are several iron absorption systems, notably near 1600$A. The Mg II lines, in the available LWP image (LWP $100$) cannot be observed due to saturation.

Hc3-1482: This is the only star in the sample to be observed with virtually all wavelengths from optical through radio. Judging from its optical spectroscopy, it is one of the coolest stars in the sample. There are no strong HeI lines in the spectrum, and numerous [Fe II] lines. The Si IV line, which is pumped by Ly$eta$, is strong. Several N I lines are also observed in the near IR, and there is weak evidence for the Ca II IR triplet in emission. This is also the only star in the sample with Na I showing P Cygni profiles. The reddening is estimated to be $E(B-V) = 1.28$ so that $A_V = 5.96$. The 12.5 flux compared with the 6 cm radio data gives a spectral index of $\alpha = 0.97$, characteristic of a marginally thin stellar wind. Several of the stars have to be observed with longer exposures than we originally obtained. Recent VLA A and B configuration observations at 6 and 20 cm have shown what appears to be a small H II region (about 5 arcsec across), probably thermal, with a flux of order 2 mJy (6 cm) surrounding Hc3-1482. The star's optical properties indicate that it possesses an extremely strong stellar wind, with $M$ likely greater than $\eta$ Cygni. The H II region appears to be thermal. Our observation of this star (SWP 28308) shows no very strong emission lines, but the exposure is exceedingly weak. This is an extremely important comparison object, since it is the only star in the sample that can be, and has been observed with the VLA.

3. The Magellanic Cloud Counterparts

All of the LMC/SMC "Zoo" sample have been previously observed with IUE during programs that ended nearly a half-decade ago. Consequently, they were all obtained with the LWR and all were obtained in a relatively short interval. Due to time constraints in the first programs (CBDSS and HLESS), a number of these spectra were not optimum. To place the Galactic sample in proper context, we wish to re-observe that subset of the Large Magellanic Cloud stars which seem to have partners in the Galactic sample. We also wish to obtain better spectra of a few stars which were not well observed during the previous years of IUE and which may also be analogs of the Galactic sample, at least judging from their optical spectra.

A subset of the LMC stars has been identified as possessing dust envelopes (S65/LMC = R56, S12/LMC, S22/LMC, S73/LMC = R66, S80/LMC = R82, S127/LMC = R126, S134/LMC = HD 38489) (ref. 6). Shore and Sandulek (ref. 2) had previously suggested that several of these were dusty on the basis of the UV continuum distributions. In addition, several of these stars show among the highest mass loss in the "Zoo" sample. Several of these stars have been flagged as being LMC analogs of the Galactic sample (Shore, et al. 1986). In addition, a few of the Galactic sample have strong dust signatures from IRAS data (Shore et al. 1988, in preparation). The majority of these stars have not been observed for at least three years and it would be most useful to see whether the envelopes still have the same structure on which the current comparison is based.

S9/LMC: This is one of the earliest stars in the Magellanic Cloud sample, and one which is similar to Hc3-40. There are no strong emission lines in the existing UV spectrum. The S/N in the original spectrum, though, is low and it would be useful to obtain a new set of LWP and SWP spectra to better determine the properties of this star.

S12/LMC: There is only a single spectrum for this star, which is known to show IR dust emission and strong P Cygni profiles in the optical (ref. 6; Shore and Sandulek 1985, in preparation [1984 CTIO observations]).

S22/LMC: This star has been observed with IUE on several occasions (there are about 6 SWP images of this star in the archives). There is no evidence of spectroscopic or photometric variability. S22/LMC shows the most extreme emission spectrum of Fe II and [Fe II] of any star in the "Zoo" sample (refs. 2, 6). The star is known to have a variable shell, with some light variations also having been observed. This star's spectrum is also analogous to the deep Fe absorption systems observed in the dense shell phase of SN 1987a and of $\eta$ Car.

S124/LMC: This star has only one, partially overexposed, SWP spectrum. It possesses one of deepest Si IV doublets of any of the sample, the lines in which are well resolved, and a very strong C IV line. There is no Si III and only weak Al III. However, the Fe II absorption is well developed.

S127/LMC: This star has the strongest Al III lines of any star in the sample, and is one of the few that has been observed at high dispersion. It is the closest spectrum in the UV, among the entire "Zoo" sample, to one of the Galactic stars, Hc3-395. Zickgraf et al. (ref. 10) have discussed it at some length, suggesting that it may be a hypergiant on the verge of rotational destruction. If so, it is important to compare this with its Galactic counterpart. While there is currently no strong evidence for photometric or spectroscopic variability, we expect that this star may have an unstable envelope and should be re-observed.

S134/LMC: This star was sufficiently deviant in our original survey to warrant separate discussion (ref. 12). Optical photometric variability has been noted (Stahl et al. 1985). One of the Galactic sample, Hc3-1138, has many of the same optical properties and a detailed comparison of the two stars would be interesting.
4. Concluding Remarks

For the Galactic stars, the data is too spotty presently and too incomplete, to quantitatively assess the degree of similarity between the stars. Individual stars appear, however, to bear striking resemblances to LMC stars, although the extent of this comparative behavior is not clear. In order to study the evolution of the most massive stars in two galactic systems of very different properties, a systematic approach, with a good time baseline, is required. This is essential, since observations have demonstrated that several of the Hubble-Sandage variables, of which these stars are the galactic counterparts, are variable on timescales of about a year, while others are only variable in times of decades.

We urge continued monitoring of these stars, at all wavelengths. They cannot fail to be interesting examples of the most massive stars and their antics.

Acknowledgements

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Late Paper
ABSTRACT

Spectra of MgII h and k have been obtained for V471 Tau at phases zero (K dwarf in front) and 0.5 (white dwarf in front). At phase zero, strong blueshifted absorption is present, suggestive of a wind from the K dwarf with terminal velocity 600-700 km/sec and mass loss rate at least three orders of magnitude greater than solar. Discrete blue-shifted absorption features occur at velocities of about 200 and 500 km/sec. At phase 0.5, the blueshifted absorption is much weaker, although still detectable.

Key words: mass loss - K dwarf

1. INTRODUCTION

V471 Tau is a detached binary composed of a K2 dwarf in a 12.5 hour orbit around a DA2 white dwarf (effective temperature ~ 35000 K [Ref. 1]). The K2 dwarf has a mass and radius of about 0.8 times solar, and absolute magnitude +5.8 (Ref. 2). Although the system as present shows little or no signs of "activity", it is regarded as a progenitor of a cataclysmic variable. The latter depend for their existence on the occurrence of rapid mass transfer from the non-compact star to the compact companion. However, there is at present no direct observational evidence for mass loss from any cool dwarf star in the field.

2. OBSERVATIONS

On August 24, 1987, the IUE satellite was used to obtain high resolution spectra of V471 Tau in the long wavelength camera. One spectrum was centered on phase zero ($\phi = 0.94-0.06$); the second was centered on phase 0.5 ($\phi = 0.44-0.56$).

In order to enhance detectability of features associated with the K dwarf, we used velocity compensation. Both exposures were 100 minutes in duration, consisting of ten segments of 10 minutes each. Between each 10 minute segment, the exposure was interrupted so that the star could be moved to a different position in the aperture. These positions were chosen so that the variation in velocity of the K dwarf due to orbital motion during the 100 minutes exposure would be compensated in the spectrum. (During the exposure around phase zero, the radial velocity of the K dwarf changed from -50 to +90 km/sec.) In planning the velocity compensation, the variation of velocity with time was assumed to be linear during the phase interval spanned by each exposure.

3. RESULTS

The MgII h and k lines in the two exposures are shown in Figs. 1 and 2. These were extracted from the IUE images by standard packages on the Goddard RDAF. The horizontal lines in both plots are weighted mean fluxes between velocities of -1000 and -3000 km/sec. We regard these fluxes as a measure of the local continuum to the blue of the Mg k line in both spectra. The continuum level is higher at phase 0.5 than at phase zero by a factor of about 2, because of the eclipse of the white dwarf during about half of the exposure at phase zero.

The abscissae scales are in km/sec relative to the k-line vacuum wavelength of 2796.35Å. Note that on this scale, the h line (with a vacuum wavelength of 2803.52Å) lies at a velocity of +770 km/sec.

In Fig. 1, the "emission feature" centered at a velocity of about +200 km/sec, and appearing to be a component of the K-line, is due to a flaw in the image.

3.1 Blue-shifted absorption

At phase zero, there is a broad and deep absorption trough on the blueward side of the Mg k line. If the terminal velocity, $v_t = 650$ km/sec. The exact value of the terminal velocity depends on how much smoothing we use in plotting the spectra, and also on the continuum level which we choose. The actual number is found to vary between 550 and 750 km/sec depending on the velocity of the K dwarf due to orbital motion during the 100 minutes exposure would be
3.2 Discrete components

At phase zero, the blueward absorption is not uniformly deep. Rather, the absorption is deepest (almost black) at velocities -200 and around -500 km/sec. The exact ranges depend, again, on how much smoothing one applies to the profiles. It is interesting that Bruhweiler and Sion (Ref. 3) have previously reported discrete absorption components in other "cool" ions (CII, SiII) at velocities of -260 and -590 km/sec.

Absorption dips around -200 and -500 km/sec may also be present in the h-line, but it is difficult to identify with certainty because of a data gap between adjacent echelle orders in IUE, and because of the flaw in the k-line.

At phase 0.5, the wind absorption is weaker than at phase zero, but is still sufficient to allow blue-shifted absorption due to the h-line to distort the k-line emission significantly.

3.3 Mass loss rate

Interpreting the blueward absorption in Fig. 1 in terms of a curve of growth, and converting from column densities to number densities using a length scale of order one K2-star radius, we find mass loss rates of a few times 10^{-11} solar masses per year. This exceeds the solar mass loss rate by some three orders of magnitude.

3.4 Nonaxysymmetric wind

Since the two hemispheres of the K2 dwarf have such different chromospheric properties, it is likely that the wind speeds from the two faces are different. One result of this, in the presence of rotation, will be to give rise to co-rotating interaction structures (CIR's) (Ref. 4) where fast wind interacts with slower wind. We propose that the two pronounced absorption dips around -200 and -500 km/sec in the Mg k-line absorption arise in velocity plateaus associated with CIR's in the wind.

According to simple kinematic concepts (Ref. 4), the CIR should form first at a radius of order \( v_w/v_r \) stellar radii (where the wind speed is \( v_w \) and the rotation speed is \( v_r \)). For V471 Tau, with \( v_r = 130 \) km/sec, and \( v_w \) of order a few hundred km/sec, CIR's should form at radial distances of a few stellar radii. The presence of dense velocity plateaus in the inner wind enhances the detectability of the mass loss from V471 Tau.

4. CONCLUSIONS

We report evidence from IUE spectra for a wind from the K dwarf in V471 Tauri with a mass loss rate some 1000 times the solar rate.

5. REFERENCES

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