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Nucleosynthesis and the Nova Outburst

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Abstract.

A nova outburst is the consequence of the accretion of hydrogen rich material onto a white dwarf and it can be considered as the largest hydrogen bomb in the Universe. The fuel is supplied by a secondary star in a close binary system while the strong degeneracy of the massive white dwarf acts to contain the gas during the early stages of the explosion. The containment allows the temperature in the nuclear burning region to exceed 10^8K under all circumstances. As a result a major fraction of the CNO nuclei in the envelope are transformed into β^+-unstable nuclei. We discuss the effects of these nuclei on the evolution. Recent observational studies have shown that there are two compositional classes of novae; one which occurs on carbon-oxygen white dwarfs, and a second class that occurs on oxygen-neon-magnesium white dwarfs. In this review we will concentrate on the latter explosions since they produce the most interesting nucleosynthesis. We report both on the results of new observational determinations of nova abundances and, in addition, new hydrodynamic calculations that examine the consequences of the accretion process on $1.0M_\odot$, $1.25M_\odot$, and $1.35M_\odot$ white dwarfs. Our results show that novae can produce ^{22}Na, ^{26}Al, and other intermediate mass nuclei in interesting amounts. We will present the results of new calculations, done with updated nuclear reaction rates and opacities, which exhibit quantitative differences with respect to published work.

1. Introduction: A Nova Explosion as a Thermonuclear Runaway

The outbursts of classical novae are caused by thermonuclear runaways (hereafter, TNR's) proceeding in the accreted hydrogen-rich envelopes of the white dwarf components of nova binary systems (Truran 1982, 1990; Starrfield 1989, 1993, 1995). For the physical conditions of temperature and density that are expected to obtain in this environment, thermonuclear burning proceeds by means of hydrogen burning from either the proton-proton chain (early in the accretion phase) or the carbon, nitrogen, and oxygen (CNO) bi-cycle (late in the accretion phase and through the peak of the outburst). If there are heavier nuclei present in the nuclear burning shell, they will contribute primarily to the nucleosynthesis and only partially to the energy production.

For solar composition material, energy production and nucleosynthesis from the CNO hydrogen burning reaction sequences impose interesting constraints on the energetics of the runaway: in particular, the rate of nuclear energy generation at high temperatures ($T > 10^8$K) is limited by the timescales of the slower *and temperature insensitive positron decays*, particularly ^{13}N ($\tau = 600$s), ^{14}O ($\tau = 102$s), and ^{15}O ($\tau = 176$s). The behavior of the β^+- unstable nuclei holds important implications for the nature and consequences of classical nova outbursts. For example, significant enhancements of envelope CNO concentrations are required to insure higher levels of energy release on a hydrodynamic timescale (seconds for white dwarfs) and thus produce a violent outburst (Starrfield, Truran, and Sparks 1978; Truran 1982; Starrfield 1995).

The large abundances of the β^+-unstable nuclei, at the peak of the outburst, have important and exciting consequences for the evolution. (1) Since the energy production in the CNO cycle comes from proton captures followed by a β^+-decay, the rate at which energy is produced, at temperatures exceeding 10^8K, depends only on the half-lives of the β^+-unstable nuclei and the numbers of CNONeMg nuclei initially present in the envelope. (2) Since convection operates throughout the entire accreted envelope, it brings unburned CNONeMg nuclei into the shell source, when the temperature is rising very rapidly, and keeps the nuclear reactions operating far from equilibrium. (3) Since the convective turn-over time scale is $\sim 10^2$ sec near the peak of the TNR, a significant fraction of the β^+-unstable nuclei can reach the surface without decaying and the rate of energy generation at the surface can exceed 10^{12} to 10^{13} erg gm^{-1} s^{-1} (Starrfield 1989). (4) The β^+-unstable nuclei decay when the temperatures in the envelope have declined to values that are too low for any further proton captures to occur, yielding isotopic ratios in the ejected material that are distinctly different from those ratios predicted from studies of equilibrium CNONeMg burning. (5) Finally, the decays of the β^+-unstable nuclei provide an intense heat source throughout the envelope that helps in driving the material off the white dwarf.

Theoretical calculations of this mechanism show that sufficient energy is produced, during the evolution described above, to eject material with expansion velocities that agree with observed values and that the predicted light curves produced by the expanding material are in reasonable agreement with the observations (Truran 1982; Starrfield 1989, 1995; Starrfield et al. 1992; Politano et al. 1995). Our recent studies have shown that it is the outbursts that occur on oxygen-neon-magnesium (ONeMg) white dwarfs that produce the most interesting nucleosynthesis and here we concentrate on those outbursts. In order to demonstrate that such outbursts exist, in the next section we briefly describe the abundance determinations for novae and provide a table of abundances determined from nebular techniques. We follow that with a section on theoretical studies of outbursts on ONeMg white dwarfs. We end with a summary.

2. Oxygen-Neon-Magnesium Novae

The production of large amounts of ^{22}Na, ^{26}Al, and other intermediate mass nuclei in a nova outburst requires that the outburst occur on an ONeMg white dwarf. Therefore, it is appropriate at this point to present the evidence that such novae exist. Although Law and Ritter (1983) first proposed that such white dwarfs could exist, it was the outburst of V693 Cr A 1981 that demonstrated that they did exist in nova systems (Williams et al. 1985). Ultraviolet spectroscopic data were obtained for this nova with the International Ultraviolet Explorer satellite (IUE) over a six month period. It was clear from the last set of spectra (which showed strong [Ne IV] 1602Å and 2420Å) that neon was enriched in the ejecta. This was later confirmed by detailed analyses (Williams et al. 1985; Andreä et al. 1994). Their results are given in Figure 1 along with those for all well studied novae.

Given these data, Starrfield et al. (1986) performed a theoretical study of accretion onto massive white dwarfs in which only oxygen was enhanced (their nuclear reaction network did not include nuclei above fluorine at that time) and showed that such an outburst would appear different from a nova with just carbon and oxygen enhanced (one that occurred on a CO white dwarf). This is because carbon has a much larger nuclear reaction cross-section than oxygen and so the TNR could occur with less accreted material on the white dwarf. At virtually the same time that they were doing their calculations, Gehrz et al. (1985) reported that the slow nova QU Vul 1984 No. 2 showed enhanced neon. These results, in combination with the IUE spectra that also showed strong neon lines (Starrfield 1988), implied that the ejecta of QU Vul were enriched in neon and magnesium as was again confirmed by detailed analyses (Saizar et al. 1992; Andreä et al. 1994). Truran and Livio (1986) then predicted that about one-third of all observed outbursts should be ONeMg novae.

Two recent outbursts have proved to be very important. Nova V838 Her 1991 was discovered on March 24, 1991 at ~5th Mag. and began a rapid decline in the optical. Although there was strong circumstantial evidence that it was an ONeMg nova (Starrfield et al. 1993), confirmation came from an analysis done by Matheson et al. (1993) who reported that both neon and sulfur were enriched in the ejecta. Their abundance determination was in good agreement with results of TNR's on massive ONeMg white dwarfs, as reported in Starrfield et al. (1992).

V1974 Cyg 1992 was the brightest nova found in outburst since V1500 Cyg 1975 and it was observed from γ-ray wavelengths to cm radio. It was observed with HST, IUE, VOYAGER, ROSAT, KAO, and pointed at, but not detected, by COMPTON GRO. The most important data were obtained by ROSAT, which followed it through its entire X-ray outburst (Krautter et al. 1995), and IUE which not only was able to study it in its fireball stage but provided a wealth of information about the evolution of its nebular spectrum (Hauschildt et al. 1994a;

Heavy Element Abundances (by Mass Fraction) in Novae from Optical Spectroscopy

Object	Year	Ref.	H	He	C	N	O	Ne	Na-Fe	Z	$(Z/Z_{\odot})$	$(Ne/Ne_{\odot})$	[Ne/Z]
T Aur	1891	4	0.47	0.40		0.079	0.051			0.13	6.8		
RR Pic	1925	13	0.53	0.43	0.0039	0.022	0.0058	0.011		0.043	2.3	6.3	13.5
DQ Her	1934	15	0.34	0.095	0.045	0.23	0.29			0.57	30.		
DQ Her	1934	7	0.27	0.16	0.058	0.29	0.22			0.57	30.		
HR Del	1967	12	0.45	0.48		0.027	0.047	0.0030		0.077	4.1	1.7	2.0
V1500 Cyg	1975	3	0.49	0.21	0.070	0.075	0.13	0.023		0.30	16.	13.	4.0
V1500 Cyg	1975	6	0.57	0.27	0.058	0.041	0.050	0.0099		0.16	8.4	5.6	3.3
V1668 Cyg	1978	11	0.45	0.23	0.047	0.14	0.13	0.0068		0.32	17.	3.9	1.1
V1668 Cyg	1978	1	0.45	0.22	0.070	0.14	0.12			0.33	17.		
V693 CrA	1981	14	0.29	0.32	0.046	0.080	0.12	0.17	0.016	0.39	21.	97.	23.
V693 CrA	1981	1	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66	35.	148.	21.
V1370 Aql	1982	10	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86	45.	296.	32.
V1370 Aql	1982	1	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86	45.	296.	34.
GQ Mus	1983	5	0.27	0.32	0.016	0.19	0.19	0.0034	0.0068	0.41	22.	1.9	0.073
PW Vul	1984	8	0.69	0.25	0.0033	0.049	0.014	0.00066		0.067	3.5	0.38	0.52
PW Vul	1984	5	0.54	0.28	0.032	0.11	0.038			0.18	9.5		
PW Vul	1984	1	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30	16.	2.3	0.70
QU Vul	1984	9	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10	5.3	23.	21.
QU Vul	1984	1	0.33	0.26	0.0095	0.074	0.17	0.086	0.063	0.40	21.	49.	11.
QU Vul	1984	2	0.36	0.19		0.071	0.19	0.18	0.0014	0.44	23.	100.	22.
V842 Cen	1986	1	0.41	0.23	0.12	0.21	0.030	0.00090	0.0038	0.36	19.	0.51	0.13
V827 Her	1987	1	0.36	0.29	0.087	0.24	0.016	0.00066	0.0021	0.35	18.	0.38	0.099
QV Vul	1987	1	0.68	0.27		0.010	0.041	0.00099	0.00096	0.053	2.8	0.56	0.98
V2214 Oph	1988	1	0.34	0.26		0.31	0.060	0.017	0.015	0.40	21.	9.7	2.2
V977 Sco	1989	1	0.51	0.39		0.042	0.030	0.026	0.0027	0.10	5.3	15.	14.
V433 Sct	1989	1	0.49	0.45		0.053	0.0070	0.00014	0.0017	0.062	3.3	0.80	0.12
V351 Pup	1991	16	0.37	0.25	0.0056	0.076	0.19	0.11		0.38	20.	63.	15.
V1974 Cyg	1992	2	0.17	0.29	0.051	0.073	0.25	0.10	0.066	0.54	29.	59.	10.

References. 1: Andreä et al. 1994; 2: Austin et al. 1996; 3: Ferland and Shields 1978; 4: Gallagher et al. 1980; 5: Hassall et al. 1990; 6: Lance et al. 1988; 7: Petitjean et al. 1990; 8: Saizar et al. 1991; 9: Saizar et al. 1992; 10: Snijders et al. 1987; 11: Stickland et al. 1981; 12: Tylenda 1978; 13: Williams and Gallagher 1979; 14: Williams et al. 1985; 15: Williams et al. 1978; 16: Saizar et al. 1996.

Shore et al. 1993, 1994; Austin et al. 1996). In addition, we were able to analyze it's outburst with two new methods. First, Hauschildt et al. (1992, 1994a, 1994b) studied the early fireball stage with a Non-LTE, spherical, expanding, model atmosphere code that was developed to study novae and supernovae. Second, Austin et al. (1996) developed a method for analyzing nova nebular spectra. It uses Cloudy (Ferland 1994) to predict emission line fluxes which are then compared to observed emission line fluxes. Ten thousand trials are run in order to find the initial conditions (electron density, electron temperature, ionizing flux, elemental abundances, ...) so that CLOUDY's predicted emission line fluxes are in "good" agreement with the observed fluxes. The first set of results have been done for V1974 Cyg and can be found in Figure 1.

Even a cursory glance at Figure 1 shows that novae ejecta are enriched in the elements which drive extremes of nuclear energy generation. The mean heavy element mass fraction for these *well studied* cases is $Z = 0.34$ (we averaged multiple determinations for the same nova). Determining the cause of the large discrepancies between some of the abundance determinations *for the same nova outburst* warrants further study, which is in progress (Schwarz et al. 1996, in preparation; Vanlandingham et al. 1996, in preparation). We also note that for at least three recent novae, V1370 Aql 1982, V2214 Oph 1988, and V838 Her 1991 (Matheson et al. 1993; Vanlandingham et al. 1996, in preparation) the ejected material was enriched in sulfur as well as neon and magnesium. We emphasize that the source of these large abundance enrichments must be matter dredged up from the underlying ONeMg white dwarf and processed through hot, hydrogen burning. The production of sulfur requires, in addition, that the white dwarf be massive. Therefore, there must be mass differences between the white dwarfs in novae such as V838 Her 1991 and those in novae such as V1974 Cyg 1992 and V351 Pup 1991 (Starrfield et al. 1992; Politano et al. 1995).

3. Theoretical Studies of Oxygen-Neon-Magnesium Novae

Weiss and Truran (1990) and Nofar, Shaviv, and Starrfield (1990), in separate and independent studies with different nuclear reaction networks but similar nuclear reaction rates, have reported the results of calculations which simulate the synthesis of ^{22}Na and ^{26}Al in ONeMg-rich novae. Their calculations were performed with the use of large nuclear reaction networks that utilized temperature, density, and time profiles which were obtained from earlier hydrodynamic simulations of the outburst.

The results of both their studies can be summarized as follows: (1) they confirm earlier findings of Hillebrandt and Thielemann (1982) and Weischer et al. (1986) that extremely low levels of ^{26}Al and ^{22}Na are expected to be formed in nova envelopes with a solar composition. This result implies that slow CO novae are not expected to contribute significantly to the abundances of either isotope in the galaxy. (2) Enrichment of only the CNO nuclei does not significantly increase the production of ^{22}Na or ^{26}Al, although CO novae may be responsible for production of some rare light nuclei. (3) Greatly increased ^{22}Na and ^{26}Al production does result from envelopes with substantial initial enhancements of ^{16}O, ^{20}Ne, and ^{24}Mg. (4) Novae with ejecta rich in material from an ONeMg white dwarf may represent an important source of ^{26}Al in our Galaxy (Starrfield et al. 1993). (5) The abundances of ^{22}Na predicted for the ejecta of novae involving ONeMg white dwarfs are sufficiently high that we may expect nearby ONeMg novae, such as V838 Her 1991, to produce flux levels of ^{22}Na decay γ-rays detectible by GRO (Starrfield et al. 1992). (6) The calculations also indicate that there should be a strong anti-correlation between ^{22}Na and ^{26}Al production in nova outbursts. (7) The degree of enrichment of ^{22}Na and ^{26}Al is a sensitive function of the temperature history (assuming equal initial concentrations of nuclei) and, therefore, the detection of ^{22}Na would provide useful constraints on the evolution of the TNR.

The results from the one zone nucleosynthesis studies must be verified by hydrodynamic evolutionary studies. In an actual event, convective mixing carries material from the nuclear burning region to the surface on very short time scales. This increases the abundances of nuclei that would have been burned to other nuclei if they had not been carried to higher, cooler layers. In addition, convection continuously brings fresh nuclei into the nuclear burning layers from cooler regions close to the surface.

Therefore, it was necessary to develop a large nuclear reaction network which includes 86 nuclei up to ^{40}Ca, and use this network, in combination with our implicit, *one-dimensional hydrodynamic computer code*, to study the consequences of accretion of hydrogen rich material onto ONeMg white dwarfs (Politano et al. 1996). A description of the current version of this code and references to earlier version can be found in Politano et al. (1996).

Table 1. Evolutionary Results

Sequence	1	2	3	4
Mass	1.00M$_\odot$	1.25M$_\odot$	1.25M$_\odot$	1.35M$_\odot$
L (10^{-3}L$_\odot$)	9.4	9.7	2.9	9.6
T$_{eff}$ (K)	20,500	25,700	12,400	30,300
Radius (km)	5379	3496	3495	2488
$\dot{M}$ (10^{-9}M$_\odot$yr^{-1})	1.6	1.6	0.8	1.6
τ_{TNR}(10^4 yr)	7.3	2.0	5.1	.9
M$_{acc}$ (10^{-5}M$_\odot$)	10.5	3.2	4.0	1.5
P$_{TNR}$ (10^{19} dynes cm^{-2})	2.5	5.2	6.5	10.0
PEAK ϵ_{nuc} (10^{17} erg gm^{-1} s^{-1})	0.2	1.0	1.1	1.9
PEAK T$_{ICE}$ (10^8K)	2.24	2.90	2.97	3.56
PEAK L (10^4L$_\odot$)	2.2	4.3	2.5	16.3
PEAK T$_{eff}$ (10^5K)	3.4	6.4	5.1	9.0
M$_{ej}$ (10^{-6}M$_\odot$)	<1.0	1.0	2.0	5.2
V$_{max}$ (km s^{-1})	45	560	1770	2320

In the work reported in Politano et al. (1995), we evolved TNR's in accreted hydrogen rich layers of white dwarfs with masses of 1.0M$_\odot$, 1.25M$_\odot$, and 1.35M$_\odot$. In Table 1 and 2 the evolutionary sequences labeled 1 and 4 are identical to the 1.0M$_\odot$ and 1.35M$_\odot$ sequences reported in Politano et al. (1995). Since those calculations were done, however, we have updated both the nuclear reactions and the opacities but concentrated on evolutionary studies only at 1.25M$_\odot$ since that is the most probable mass for the white dwarf in the V1974 Cyg binary system

(Starrfield et al. 1995). However, we redid the calculations for the 1.25$M_\odot$ mass white dwarf reported in Politano et al. with the only change being to increase the convective efficiency from α equal 1.0 to 2.0 (ratio of mixing-length to scale height). This new sequence ejected $\sim 10^{-6}M_\odot$ while the sequence reported in Politano et al. did not eject any material at this mass. Note that for sequences 1, 2, and 4, we assumed that the rate of accretion onto the white dwarf was 10^{17}gm s^{-1} (1.6 x 10^{-9} $M_\odot$yr^{-1}). For sequence 3, we used a value of half that: 5 × 10^{16}gm s^{-1} (8 × $10^{-10}M_\odot$yr^{-1}). In all four sequences, we used an initial abundance of ONeMg nuclei equal to 50% of the envelope material (by mass). The remaining 50% consisted of a solar mixture of the elements. We assumed that this composition resulted from the mixing of the accreted material with core material.

There were two other major differences between sequence 3 and the other three sequences. This evolutionary sequence was done using the *carbon-rich* OPAL opacities (Iglesias and Rogers 1993) and updated nuclear reaction rates (Van Wormer et al. 1994; Herndl et al. 1995). Both of these changes had major effects on the evolution and a detailed report will appear elsewhere (Starrfield et al. 1996, in preparation). Here we mention two effects. First, the OPAL opacities are larger than those used in our previous studies. Therefore heat is trapped more effectively within the nuclear burning layers, the temperature rises faster, and it takes less time to reach the TNR . For equal mass accretion rates, the sequence with the OPAL opacities accretes less material. Second, the new reaction rates, as reported in Van Wormer et al. and Herndl et al., are much larger around mass 26 than those used previously. This implies that, for a given white dwarf mass, the amount of ^{26}Al produced during the evolution will be smaller than we found in our previous studies (see Table 2).

Table 2. Ejected Abundances (by Mass Fraction)

Sequence	1	2	3	4
Mass	1.00$M_\odot$	1.25$M_\odot$	1.25$M_\odot$	1.35$M_\odot$
X	.33	.30	.21	.27
Y	.17	.19	.27	.20
^{12}C + ^{13}C (10^{-2})	.94	4.3	1.1	3.4
^{14}N + ^{15}N (10^{-2})	2.0	2.5	7.9	8.8
^{16}O + ^{17}O (10^{-2})	11.8	7.0	5.4	1.1
^{18}F + ^{19}F (10^{-4})	1.7	4.0	7.6	25.9
^{20}Ne + ^{21}Ne + ^{22}Ne	.25	.23	.23	.17
^{22}Na (10^{-3})	.05	1.7	2.7	5.7
^{24}Mg + ^{25}Mg + ^{26}Mg (10^{-2})	5.9	3.8	0.6	4.4
^{26}Al (10^{-3})	19.6	9.4	1.0	7.4
^{27}Al (10^{-3})	14.0	16.0	13.7	19.0
^{28}Si + ^{29}Si + ^{30}Si (10^{-2})	1.6	5.8	9.9	5.3
^{31}P (10^{-4})	0.02	40.2	82.0	202.0
^{32}S (10^{-4})	1.1	29.4	55.0	289.0
^{36}Ar (10^{-5})	1.9	2.1	.5	40.9

Here, we discuss the results for the evolutionary sequence which examined the consequences of accretion onto a 1.0$M_\odot$ white dwarf (Sequence 1 in both Tables) since it is that sequence which produced the largest amount of ^{26}Al. We have not done any new studies at this white dwarf mass but expect that the amount of ^{26}Al will be only slightly reduced from the value reported in Table 2. We terminated the accretion phase when the temperature at the interface between the core and the accreted envelope (hereafter, ICE) had reached 45 million degrees and the rate of energy generation had reached, $\epsilon_{nuc} \sim 1.0 \times 10^9$ erg gm^{-1} s^{-1}. At this time, the abundance of ^{26}Al, which was zero in the initial model, had increased to 5.2×10^{-7} (all abundances in this paper are quoted as mass fractions). The abundance of ^{27}Al, which was initially 1.6×10^{-5}, had not changed at this time. We also found that the convective region, which first appeared when T_{ICE} reached about 30 million degrees, had grown to a region which extended to 200 km above the ICE (75 km below the surface).

By the time T_{ICE} had reached to 2×10^8K, the abundance of ^{26}Al had increased to 1.3×10^{-2} at the ICE. It was being produced by the reaction sequence: ^{24}Mg(p,γ)^{25}Al($\beta^+\nu$) ^{25}Mg(p,γ)^{26}Al. The isomeric state was not important. The peak luminosity is given in Table 1 and the final abundances (mass fraction) for some of the nuclei in our network are given in Table 2. Except for ^{26}Al, ^{27}Al, and a few other nuclei, we summed over the most abundant isotopes in order to keep the table small. Since most of the ^{26}Al comes from the decay of ^{25}Al followed by the proton capture on ^{26}Mg, its abundance continued to increase even after peak temperature had been reached.

The expansion of the nova envelope gradually slowed until, after a few hours, the surface layers were moving at speeds of only a few km s^{-1}. It was clear that the energy production during the TNR was insufficient to *explosively* eject the shells. In addition, the luminosity was only about half the Eddington luminosity (solar mixture, electron scattering opacity) so that it appeared that radiation pressure driven mass loss was unimportant. That this is not true, however, was shown in an important paper by Hauschildt et al. (1994). They found that the very large opacity from the iron group elements ("iron" curtain) in an expanding medium reduces the "effective" Eddington luminosity by factors of as much as 100. This implies that radiation pressure is sufficient to drive off a significant fraction of the envelope when the iron group opacity is largest. This occurs around the time of maximum light in the optical (Shore et al. 1994). The expanding iron group opacity is not in the OPAL tables and was not included in our calculations. We expect, however, when it is included a large fraction of the accreted envelope will be ejected during the early stages of the outburst.

We also neglected common envelope evolution in these calculations which should act on material that extends past about 10^{11}cm. Therefore, although in Table 1 we list the amount of mass ejected as nearly zero, in fact, more than $1.4 \times 10^{-5} M_\odot$ lie beyond a radius of 10^{11}cm and will ultimately be ejected in a slow nova outburst. The abundances given in Table 2 have been determined assuming that all of the material at radii exceeding 10^{11}cm has been ejected.

The results of our simulations show that, as we go to higher mass white dwarfs, the violence of the outburst increases. In fact, the 1.35$M_\odot$ simulation results in material being ejected during the explosive phase of the outburst and we do not have to depend on either enhanced opacity caused by the "iron" curtain or common envelope evolution to drive mass off the white dwarf. We also note that, for a $1.35M_\odot$ white dwarf, the peak temperature during the evolution is high enough ($T = 3.56 \times 10^8$) for significant nucleosynthesis, involving the intermediate mass nuclei, to occur.

This is confirmed by an examination of the abundances of some of the more massive nuclei shown in Table 2. Note, first, that the abundance of ^{26}Al declines as the white dwarf mass increases while the abundance of ^{22}Na increases as the mass of the white dwarf increases. This suggests that the novae which produce the largest enrichment of ^{26}Al may not be the same novae that produce enhanced ^{22}Na. In addition, as we proceed to higher white dwarf masses, the abundances of ^{31}P, ^{32}S, and ^{36}Ar increase to very large values. All of these nuclei must be produced as the result of "slow" (relative to the rates which dictate energy generation) proton captures on ^{24}Mg over the few minute lifetime of the explosion. We also call attention to the behavior of the light nuclei in our results. ^{12}C increases in abundance with white dwarf mass, but ^{16}O decreases in abundance. In contrast, the total neon abundance remains virtually constant. This could be the explanation of the puzzling feature that all of the observed ONeMg novae always show strong neon lines even when the O, Mg, or Al lines are weak.

4. Summary

In this paper we have examined the consequences of accretion of hydrogen rich material onto ONeMg white dwarfs with masses of $1.0M_\odot$, $1.25M_\odot$, and $1.35M_\odot$. These results, in combination with one zone nucleosynthesis studies have demonstrated that novae produce ^{22}Na, ^{26}Al, and other intermediate mass nuclei in astrophysically interesting amounts. Specifically: 1) Hot hydrogen burning on ONeMg white dwarfs can produce as much as 2% of the ejected material as ^{26}Al and 3% as ^{22}Na. 2) The largest amount of ^{26}Al is produced in the lowest mass white dwarfs, which according to our evolutionary calculations, should eject the largest amount of material. The observations of QU Vul, a slow ONeMg nova, indicate that it has ejected about $10^{-3}M_\odot$. It must be emphasized, however, that such a large amount of ejected mass is inconsistent with the amount predicted to be accreted onto a typical ONeMg white dwarf whose mass is expected to exceed $1.25M_\odot$. 3) The largest amount of ^{22}Na is produced by the highest mass ONeMg white dwarfs nova systems. These novae are predicted to be among the fastest and most luminous novae. In addition, the abundance of ^{22}Na is sufficiently high for its presence to be included in the energy budget of the ejected material. 4) There cannot be large numbers of QU Vul and V1974 Cyg type novae (slow ONeMg) in the galaxy since, if there were, the observed γ-ray emission from ^{26}Al would be far higher. 5) If QU Vul and V1974 Cyg novae are rare, then we are faced with the disquieting possibility that the ^{26}Al in the solar system, observed through the abundance of its daughter, ^{26}Mg, may have either come from a single event, or not from novae at all.

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