EUROPEAN REGIONAL
ASTRONOMY MEETING OF THE IAU
Praha, Czechoslovakia August 24-29, 1987

INTERPLANETARY
MATTER

Edited by
ZDENĚK CEPLECHA, PETR PECINA

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INTERPLANETARY MATTER
A selection of 6 images of the nucleus of Comet Halley. The resolution improves from 600 to 90 m per pixel. (c) Max-Planck-Institut fuer Aeronomie. Courtesy H.U. Keller.

This image of the nucleus of Comet Halley is composed of 7 images taken from Giotto on 13 March 1986. Several features such as a mountain, a chain of hills, a crater or jets can be seen in the originals. (c) Max-Planck-Institut fuer Aeronomie. Courtesy H.U. Keller.
10th EUROPEAN REGIONAL ASTRONOMY MEETING OF THE IAU
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PREFACE

One of the main topics of the 10th European Regional Meeting of the International Astronomical Union, held in Prague during 23 – 29 August 1987, was THE COMPLEX OF INTERPLANETARY BODIES.

As the title indicates, the problems in fore-ground were the interrelations, interactions, and evolutionary processes working in different types and systems of interplanetary objects. The interplanetary population covers an immense mass range of 40 orders of magnitude and, as a whole, is only detectable by completely diverse observing techniques, in different environments: comets and asteroids in the interplanetary space, from the whole earth; meteoroids in the upper atmosphere, from limited areas on the earth; and the finest dust in spacecraft-borne detectors. The gaps between the relevant mass ranges are diminishing with the development of observing techniques, but are still there and attract special attention. As to the evolutionary scale, the interplanetary population includes both the most pristine matter preserved since the formation of the solar system, and the most recent products of intricate disintegration processes. The physical and dynamical history of each minute dust particle goes far back to its original, much larger parent body.

The spacecraft encounters with comet Halley have supplied us with a wealth of information, and many new exciting results. However, at the same time they have posed many new problems, awaiting a correct explanation. With this in view, it became obvious that our meeting should concentrate on more general problems, rather than on the properties of individual objects (such as their orbits, lightcurves, spectra etc.), which provide just the fundamentals for further studies.

Owing to the rapidly increasing interest in this research area, stimulated by the first cometary missions and current advances in measuring and computing techniques, our topical sessions attracted over 100 participants from 20 different countries. From among the plenary meetings, with still higher attendance, two were devoted to problems closely related to our area. Their proceedings are included at the beginning of this volume. The invited discourse by J. Rahe summarizes the main results of the worldwide cooperative efforts connected with the recent apparition of COMET HALLEY. It covers both the unique ensemble of space missions and the ground-based International Halley Watch. The review of the PHOBOS MISSION, presented by B. Valniček, describes another unique space project to be realized in the near future, in broad international cooperation.

The main part of this volume consists of the papers presented at six half-day sessions on the COMPLEX OF INTERPLANETARY BODIES. One of them was held jointly with the topical session on the RESONANCES; for the papers given there, they refer to the volume of TS-3 of this series. Altogether, 11 invited reviews, 29 contributed papers and 17 posters were presented. Since there was a great interest in having these proceedings published as quickly as possible, we had to put a strict deadline for the receipt of the camera-ready typescripts. Papers which did not meet this requirement had to be left out, to our regret.

For the same reason, there was no refereeing of the manuscripts, and only a few papers were retyped by the editors. At the end of each paper, and abbreviated discussion record is appended, as prepared from the question and answer forms. We believe that, in spite of its conciseness, this record may give the reader a complementary insight into the so far unresolved problems and controversial implications. However, it is clearly insufficient to let him feel the beautiful cooperative atmosphere of the meeting, created by all its participants and guests.

The other topics of the 10th European Regional Meeting of the IAU were published in four other volumes. The survey of all papers presented and published in all five volumes are contained in "Program of the Meeting and Directory of the Proceedings", Publication of the Astronomical Institute of the Czechoslovak Academy of Sciences, No. 65.

It is a most pleasant duty to thank all the colleagues who have contributed to the success of the meeting. The members of the organizing panel P.B. Babadzhanov, Z. Cepelche, P. Pecina, P. Farinella, H. Fochtig, and H. Rickman have significantly contributed to the outline of the program, and alternated in chairing the individual sessions. The authors of the invited reviews, as identified in the Table of Contents, have outstandingly summarized our present state of knowledge in the individual research areas, and the authors of the contributed papers have presented many important new results and ideas. The local organizers Z. Cepelche and P. Pecina have excellently managed all the organizational and editorial work in preparing this book they were assisted by P. Spurný, D. Pivová, L. Úrzkovičová, H. Cepelcheová and J. Žavrel.

The kind sponsorship of the International Astronomical Union, the European Physical Society, and the Czechoslovak Academy of Sciences, and their generous travel grants to a number of participants, are also acknowledged with thanks.

Č. Kresák

III
ABSTRACT

Since its recovery in 1982, Comet Halley has been the focus of an unparalleled global scientific effort of exploration. Remote and in-situ measurements were conducted from the ground, from Earth orbit, from Venus orbit, from interplanetary space, and from the comet itself. Many discoveries, such as the presence of an unexpectedly large and dark nucleus or the abundance of organic material, have led to major changes in our ideas about the general nature of comets. In this report, results of various studies are summarized.

INTRODUCTION

During its 30th historically recorded and fourth predicted apparition in 1986, Comet Halley was observed from the ground by more than 1,000 professional astronomers in over 50 different countries. In addition, the comet was visited by six spacecraft from four space agencies, carrying a total of fifty scientific instruments.

In spite of this tremendous effort, it is even now -18 months after the comet's perihelion passage-impossible to present a coherent picture of Comet Halley; instead, there are more pieces of a steadily growing puzzle and it will take many more months, if not years, before a comprehensive picture is available.

Results of the Comet Halley measurements from the ground and from space have recently repeatedly been reviewed. For more detailed references, the reader is referred to the Proceedings of the Heidelberg Symposium "Exploration of Halley's Comet" (ESA SP-250, 3 volumes; 1987) and the special issues of Nature (May 1986) and Astronomy and Astrophysics, 1987. Since at the present conference special emphasis was given to the results of ground-based measurements, it was decided to discuss in this paper especially with the in situ measurements.

IN SITU MEASUREMENTS

Halley's Comet moves in a retrograde orbit around the Sun which is inclined at 162 degrees to the ecliptic plane. All spacecraft flybys occurred around the time the comet crossed the ecliptic plane on March 1986 (descending node) with velocities of at least 68 km/sec relative to the comet. At such speeds, even for the dual bumper shield equipped Giotto spacecraft, an impact with a 0.001 gram particle could cause considerable damage to the instruments or change the orientation of the spacecraft spin axis. The Japanese spacecraft Suisei was hit by two milligram-sized particles within about 20 min before closest approach, reorienting the spacecraft spin axis by nearly one degree, but causing no damage to either spacecraft or its scientific instruments. For the Vega spacecraft, a severe dust particle bombardment damaged 45% of the solar cells for Vega 1 and 80% for Vega 2 were, but most experiments continued to operate after the encounters. Giotto approached the nucleus to within 600 km, but dust impacts caused a nearly 1 degree nutation of the spin axis shortly before the encounter. Several experiments continued to work after the flyby but were shut down when the post encounter data gathering phase was completed.

The spacecraft encountered the comet at different times and at different distances, ranging from about 600 (Giotto) to about 30 million (ICE) km. The time of the in-situ measurements in the cometary environment typically lasted a few hours for each spacecraft. The comet's heliocentric distance ranged for the time of the encounters from 0.8 to 0.9 AU. More than 100 scientific institutes and over 500 scientists from all over the world were involved in these missions.

All spacecraft were targeted to the nucleus on the sunward side, the side where all activity originates. The cameras onboard the two Vega and the Giotto missions obtained for the first time direct images of a comet's nucleus. It appeared as a single solid body of irregular elongated shape-comparable to a giant peanut or potato, both larger (about 16x8x8 km) and darker (albedo lower than 4%) than previously thought, making it one of the darkest objects in the solar system. Gas and dust emanate from only a few regions from the sunlit side of the nucleus.

An important new result is the detection of infrared radiation from...
the nucleus region by the infrared spectrometer onboard Vega 1. The corresponding temperature was found to be about 300 K, i.e. about 100 K higher than the sublimation temperature of water ice, indicating that the nucleus surface is covered by a sublimating layer of dark, porous refractory substance which is consistent with the observed low albedo. The thickness of the dust layer is unknown and could range from less than a cm to several ten meters; it might in fact vary considerably from one area to the other.

Before the in situ measurements, cometary dust was thought to be composed of certain carbonaceous chondrites, i.e. rare stony meteorites which contain small amounts of carbon. A detailed analysis of the dust particles revealed that the mean elemental abundances of several thousand grains are very similar to abundance ratios of chondrites, with the exception of those particles which are largely made up of C, H, O, and N-light elements with atomic masses of less than 20. The Heidelberg team invented the acronym "CHON" for these dust particles. Their density is 0.1 to 4 gram/ccm, and they contribute up to about 1/3 in weight to the total dust mass. They may form tar-like substances which could be a reason for the dark nucleus. The CHON particles have cosmic abundance in which carbon is about eight times more abundant than in carbonaceous chondrites. This result may also solve an old puzzle: Before the in situ measurements were made, observations indicated that carbon (relative to oxygen) was about 4 times less abundant than in the cosmic abundance. Now it appears that the missing carbon is "locked up" in the CHON particles.

Most of the CHON particles are probably composed of organic matter. M. Greenberg has suggested laboratory that organic material can be formed out of cometary matter. He postulates that submicroscopic silicate cores are covered by organic coats. These building blocks form loosely connected larger particles which is in agreement with the low density found by the dust experiments.

The in situ measurements of the dust particle density of about 0.1 to 4 gram/ccm agree also well with the average particle density of 0.25 gram/sec measured in the meteor streams of the Orionides and Aquarides which are both produced by Halley.

The deuterium-to-hydrogen ratio is estimated to be between 0.6 and 4.8 x 10^{-4}, a value which is higher than the one in the interstellar medium and in the giant planets Jupiter and Saturn, but which is in good agreement with the one found in the atmospheres of Titan and Uranus. The 18O/16O ratio of 0.0023 agrees with the terrestrial value, but there appears to be a large uncertainty about the 12C/13C value.

Another surprise was the high abundance of very small particles. Ground-based optical and infrared observations had provided practically no information about particles smaller than 0.1 of the meter. Their number was expected to be very small. The detectors onboard the spacecraft found, however, that their abundance increased considerably towards smaller sizes, and Giotto measured specks of matter of 10^{-17} gram which were perhaps only one millionth of a centimeter -i.e., about 100 atoms- in diameter.

While most astronomers were probably convinced that the comet nucleus must be mainly water ice and dust particles, Halley was the first comet in which water vapor streaming from the nucleus at velocities between 0.8 and 1.4 km/sec could be observed. At the Vega 2 encounter, about 1.6 tons of water were emitted from the nucleus; when Vega 1 passed the nucleus, twice this amount was produced, indicating that 80-90% of the nucleus consists of water ice and dust.

Giotto and the two Vegas detected carbon dioxide, but it had only 2-3% of the water abundance. Measurements from IUE and from sounding rockets, on the other hand, found considerably more CO, about 10% the abundance of water. Carbon monoxide and dioxide vaporize at much lower temperatures than water ice. Their presence could explain why comets develop comas while still far away from the sun. It is interesting to note that most of the carbon monoxide does not leave the nucleus in gaseous form; it appears to escape instead from the fine dust particles which are heated by the solar radiation in a region of about 10,000 km. The expansion velocity of the gas was determined to 800 m/sec at 2,500 km distance from the nucleus; it increased steadily to 1,000 m/sec at 20,000 km distance. In March 1986, a coma brightness outburst was followed by a large flare-up in CO+, CO2+ and dust; the water production, however, remained essentially constant during that time. This observation indicates that CO and CO2 were involved in this outburst and that pockets of these and similar volatile are perhaps present in the cometary nucleus. Other measurements from the ground and from IUE confirmed these considerable brightness fluctuations which occurred on a very short time scale.

Another radical, CN, was found in strange jets which remained narrow and well-defined for up to 60,000 km but
which did not coincide with the jets made of visible dust. The CN radicals apparently did not come from the nucleus directly but from streams of excometary material (in particular unobservable) particles which may consist of CHON material.

Combining the results from the different measurements, one finds for Comet Halley the following distribution of the major molecules: 80% water, 10% carbon monoxide, 3% carbon dioxide, 2.5% methane, 1.5% ammoniac, 0.1% cyanide.

Before the encounters, the density of the nucleus material was estimated to be about 1.2 gram/ccm. Now it turned out that the larger dust particles are aggregates of submicron sized particles. The nucleus must be about half "empty" space, perhaps similar to freshly fallen snow, and instead of calling it a "dirty snowball", F.L. Whipple called it recently a "dirty snowdrift" that somehow become compressed over time. The low packing density results in a very low heat conductivity between the outer dust layer and the ice-dust mixture underneath.

Material which is more volatile than water is still present in Halley's Comet and causes pronounced activity at distances from the sun (3-5 AU) where water ices are not affected. One can perhaps conclude that the nucleus has not been heated during and following its formation. Since some of the elements and compounds observed in Halley can have solidified only near absolute zero, the nucleus must have formed in an area reaching from the outer planets to thousands of AU away from them.

Although methane is a low temperature condensate, it was found to be abundant in the outer surface layers, supporting the idea that the cometary material is made up of low temperature pristine solar nebula matter. When going around the sun, the outer layers are lost and new fresh material is exposed.

The larger size of Halley's nucleus does not imply that the comet produces significantly more material. Earlier calculations about the contribution of comets to the amount of interplanetary dust in the ecliptic plane do apparently not need to be altered, and the question still remains to be answered whether comets alone can supply the interplanetary dust or whether a major contribution from asteroids is required as well.

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Drs. Kresak and Kresakova have discussed this problem in detail during this meeting.

The rotation period of Halley's nucleus is even now not definitely established. The Lyman-alpha imaging sensor of Suisdi e.g., detected a
comparison: the terrestrial magnetic field at the poles is 60,000 nanotesla, the interplanetary magnetic field is 8 nanotesla).

GROUND-BASED MEASUREMENTS

More than 1000 professional astronomers in 51 countries and almost 1000 amateur astronomers provided a coherent set of ground-based observations of Halley's Comet, covering the period from the comet's recovery on 16 October 1982 until the present time. The most important contribution of the International Halley Watch (IHW) will be to provide a record of the 1982-1990 apparition in different wavelengths and with high temporal resolution. Ground-based measurements have substantially complemented and extended the in situ "snap shot" like spacecraft data and provided insight into Halley's long-term evolution and short-term activity variations. For instance, only by combining ground-based brightness (product of size and albedo) measurements at the time of recovery with the space-based determinations of the nucleus size, was it possible to derive the nucleus' albedo.

A historic example of this collaboration is the "pathfinder" concept: Targeting a spacecraft close to a comet is a major problem since the nucleus is hidden by the dust and gas in the coma. Earth-based astrometry of Halley's nucleus position had an accuracy of about 500 km. Since the two Vega spacecraft encountered Halley's Comet before Giotto, a considerably improved nucleus position was obtained from Vega with the help of NASA's deep space network. Giotto achieved a flyby distance of 600 km with an uncertainty of only 40 km.

CONCLUSION

When Halley will disappear again into the outer solar system by the end of this decade - the Hubble Space Telescope, however, should be able to follow the comet up to its aphelion and back to perihelion in 2061 - it will be the most thoroughly studied comet ever. More data has already now been collected on Halley than on all other comets together.

The first predicted return of Halley's Comet demonstrated the power of scientific imagination and knowledge. The 1986 return triggered an unprecedented and unparalleled international cooperation on the ground and in space. It has brought together the largest number of scientists ever to combine efforts in a single astronomical project. It might serve as a model for future international cooperative programs.
Light curve of Halley's Comet for 1985-1986, normalized to 1 AU (Courtesy C.S. Morris).

Left: Magnetic field and cometary ion observations) within 25,000 km from the nucleus as measured by Giotto (from ESA BR-27, 1987). 16,400 km before closest approach (CA), the magnetic field magnitude reached a maximum of 57 nanotesla (magnetic pile-up region), decreased afterwards rapidly to essentially zero inside the contact surface at 4,700 km, and increased again after crossing the contact surface at 3,800 km after CA. At the same time, the ion temperature (middle panel) and velocity (upper panel) decreased. When crossing the contact surface (C), the temperature dropped by nearly 2,000 K; at the same time an outward flow of cometary ions with 1 km/sec was noticed.

Right: Ion mass spectra obtained from Giotto outside the contact surface (top) and inside (bottom), revealing considerable changes in the ion composition (from ESA BR-27, 1987).
Mass spectra of two dust particles observed from Vega, illustrating the extremes in the ratio of light elements (C, H, O, N) to heavier elements (Mg, Si, Fe). In terms of ion counts, this ratio is 24 for the upper figure and 0.07 for the lower figure (Courtesy J. Kissel).

Cometary ions observed from Giotto's Implanted Ion Sensor in three different directions (from ESA BR-27, 1987). The middle panel refers to the direction of the solar wind: at large distances the solar wind is undisturbed. Closer to the nucleus the solar wind is decelerated and the distribution broadens. Very close to the nucleus the solar wind is deflected away from this panel's viewing direction (for more details, see the special Halley volume of Astronomy and Astrophysics).
THE PHOBOS MISSION
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ABSTRACT
The complex space experiment Phobos will consist of two space probes carrying more than twenty experiments each. The primary purpose of the mission, launched in June 1988, is the exploration of the Mars satellite Phobos and of the planet itself. Various methods are used, including landing on the satellite and activation of its surface minerals by laser beam. During orbiting around Mars, the atmosphere of the planet will be studied. The secondary purpose is to study solar activity during the flight from Earth to Mars, gathering informations on solar wind, interplanetary shock waves, and gamma bursts. Solar X-ray activity will be monitored and solar corona observed in X-rays; stereoscopic studies of the Sun will be made.

The coordinator of the experiment is the Space Research Institute of the Academy of Sciences of the USSR, the other participants are from Austria, Bulgaria, Czechoslovakia, Finland, France, German Democratic Republic, German Federal Republic, Hungary, Poland, Sweden, Switzerland and ESA.

THE PURPOSE OF THE PHOBOS MISSION
This is the first space expedition in which a small body of the solar-system will be studied from aboard a spacecraft passing above the surface several meters only. The Martian satellite Phobos has been chosen as an object of studies because it is highly probably a trapped asteroid body in primordial state what can give useful informations about the conditions in which the Solar system was formed.

The solution of scientific problems of origin and evolution requires many new data, which can be obtained by direct measurements. Essential are mass and isotopic composition, different physical characteristics of the surface, as spectral, electrophysical and regolith thickness. The best solution seems to be the use of different distant research methods.

Simultaneous study of the planet Mars is supposed. This includes studies of surface, atmosphere, ionosphere and magnetosphere.

During all time of the active life of space probes the parameters of interplanetary space and of the solar-wind are registered. The constant orientation of space-probes Phobos with one axis directed towards the Sun offers the possibility for the observation of the Sun.

THE CONCEPTION OF THE PHOBOS-MISSION AND THE SPACECRAFT
Two spacecrafts are prepared for launch in June 1988 (see Fig. 1). They will reach Mars in 200 days, at the beginning of 1989 and circulate around the planet on long elliptic orbit with pericenter 4200 km (1 revolution 3 days). After 25 days this orbit will be changed to the ellipse with pericenter 9700 km for 30 days. Finally, the ellipse will be transformed in circular orbit with 9700 km pericenter (1 revolution 8 hours).

Fig. 1
This will be stable orbit for realization of maximum of measurements (Fig. 2). This orbit gives the possibility to descent at second circular orbit, identical with the aid of correcting engine and following the laser guiding telemeter for approximately 15 minutes to fly over the surface of Phobos in the high-corridor 30-80 meters. During this short period active experiments will be performed. The relative velocity of the spacecraft to the surface of Phobos will be 2-5 meters sec⁻¹.
For this mission a new generation of spaceprobes is prepared (Fig. 3).

**EXPERIMENTAL EQUIPMENT FOR THE STUDY OF PHOBOS**

The most important during the Phobos-mission is the hovering of the spacecraft over the surface of the satellite. During this 20 minutes interval following program must be realized:
- study of the mass and isotopic composition of Phobos regolith
- measure the topography and texture of the surface
- electrophysical, spectral and polarization characteristics must be determined.

Following scientific payload will be applied to perform this program: laser-beam remote system, secondary ion mass-analyzer, radar system and videospectrometer.

a/ Laser-beam mass spectrometer LIMA-D

The possibility to generate accelerated ions under heating of the surface material is used (see Fig. 4).

---

**Fig. 2**

For this mission a new generation of spaceprobes is prepared (Fig. 3).

**Fig. 3**

It has a 3-axis orientation, with the axis S directed to the Sun, to ensure good isolation of Solar panels C. The part A contains scientific equipment and at the base of the probe the engine and fuel containers are placed. High gain parabolic antenna is at the top of the probe for transmission of telemetric data. Accuracy of the stabilisation of the probe is ±10°.

**Fig. 4**

Laser L is emitting light pulses of the duration 10 nsec each 5 sec with energy 0.5 J (wavelength 1060 nm). At the surface F of the Phobos a light-spot of 1.5 mm is formed, with energy density $10^9$ W cm$^{-2}$. Accelerated ions are generated here and scattered omnidirectionally. One part of the ions is entering the entrance of mass spectrometer MS flying on the space-probe, focused in the electric field and registered by the sensor. The good function of this complex is ensured only when the light-spot of the laser-beam is still good focused on the Phobos-surface. To realize it, a laser rangefinder is measuring with cycle 20 Hz the distance spacecraft-Phobos and focusing system is automatically adjusted. Electronic package E contains indispensable logic systems for coordination of functions between L, MS and range-finder and for processing of the results which are prepared for the main memory of the spacecraft.
b/ Secondary - ion mass - analyzer DION

Secondary ions SI (see Fig. 5) are generated in regolith of Phobos by charged crypton ions IF generated onboard of the spacecraft. Ion-generator IG is providing ion flux with energy 3 keV (5 mA, giving in a mean distance 50 meters with divergence angle 20° a ion-spot about 20 meters in diameter. Secondary ion energy is distributed over the range from 0 to hundreds of electronvolts. Injection pulses 1 sec long are repeated every 5 sec and the quadrupole-mass-analyzer MS is recording secondary ions. Each mass-spectrum is recorded in the time not longer as 1 sec. The mass-spectrometer self can be used also without ion-generator, with solar-wind ions as a primary ion-source.

c/ Radar system experiment GRUNT

The subsurface sounding of the soil of Phobos will be performed using a three-channel radar system, permitting the sounding in different depths, depending from the frequency used. So with the frequency 2 MHz the depth 1000 meter can be reached. At 130 MHz it will be 10-100 m and at 500 MHz 1-10 m (see Fig. 6). The frequency 2 MHz will be used also for the sounding of the Marsian ionosphere.

d/ TV spectrometer system FREGAT

Three channel TV camera (see Fig. 7) can in 3 different colours obtain the image of the same area above which the spacecraft is flying. As image detector CCD elements are used. One part of this device is a panoramic videospectrometer VS with the rectangular slit whose long side is in the direction perpendicular to the translation motion of the space probe. It is working in 14 spectral bands in the range 400 - 1000 nm. Input objectives of the cameras and of the spectrometer have focal length 18,5 mm, relative aperture 1:2,5 and field of view 350. In the front of the objectives is a tilting mirror M, which permits in the angle-interval 90° observation of the surface below the spacecraft. The information of this optical complex is recorded with videotape recorder with 2 Mbit/sec speed and the playback for the telemetry transmission is working with 4kbit/sec.

For the function and good results of this instrumental complex is mostly important the mode of the work of the spacecraft. The orbit of the spacecraft is in this case only 30 km higher as the orbit of Phobos (see Fig. 8). For the observation must be descending manoeuvre realized to the nearest proximity of the moon's orbit and the spacecraft must be hovering some 50 meters above the surface of the moon under control of the laser range-finder.
During the period of the hovering over Phobos will be let down also two small landers: one will be jumping on the surface to have the possibility change his place, the second one will be fixed and long-living. Both landers are telemetring all informations to the main station orbiting around the planet.

OTHER SCIENTIFIC PROGRAM OF THE PHOBOS-MISSION

Experimental instrumentation of Phobos space-probes will be used also for the exploration of the planet self. It will be the radar and TV spectrometer. Onboard will be equipment for remote exploration of the thermic properties of the planet by means of radiometric method in infrared. Using excitation by galactic cosmic rays, the gamma-spectrometry of the surface material of the planet can be used. By the spectrometric observation of the Sun in the tangential direction the study of chemical composition of the Mars-atmosphere is prepared (see Fig. 9).

By means of the radar equipment the ionospheric study will be realized. Magnetometric complex is applied for study of interplanetary magnetic phenomena and of the magnetic field of the planet self. Plasmatic phenomena are studied by different methods and five experiments are prepared for large spectrum of measurements of ions and charged particles in interplanetary space during the flight and orbiting of the probes.

Because the lasting orientation of the probes to the Sun a system of Solar experiments will be performed. The most important is the complex solar telescope TEREK, working as X-rays imaging telescope, white-light coronagraph and EUV-spectrometer. X-ray photometer is used for steady registration of the integral X-ray flux and special instrument is used for the registration of solar oscillations. Also detection of cosmic gamma-bursts is prepared.

Total 23 experiment are prepared for each Phobos-probe. This is very complex program for the study of Mars, his moon Phobos, interplanetary space, solar wind and the Sun.

CZECHOSLOVAK PARTICIPATION ON THE PHOBOS-PROJECT

Czechoslovakia is realizing the general construction of the laser-beam generator for LIMA-D experiment with focusing device for the power-laser. This is very delicate work because high precision of moving parts and controls is required.

Main parts of the solar program for the Phobos mission has been proposed of Czechoslovakia, where is realized the imaging X-ray telescope and white-light coronagraph for the TEREK-experiment. Also X-photometer, using rich experience of former Prognoz-missions, for integral flux of solar X-rays is prepared in Czechoslovakia and the participation in the measurements of plasma phenomena exists.

Phobos project is good example of big international cooperation. Intercosmos and European Space Agency have united 12 countries for realization of this scientific and technological project: Austria, Bulgaria, Finland, France, German democratic republic, German federal republic, Hungary, Poland, Sweden, Switzerland, Soviet-union and Czechoslovakia. His realization will be nice document of the goodwill of scientists for peaceful international cooperation.

General remark to the pictures: in all of them E means Earth, S-the Sun, M-Mars, F-Phobos.
COMETS
Theories of the origin of the Oort cloud are examined in the light of recent observations of comets and of star-forming environments, and some popular hypotheses are found to meet with difficulties. In particular chemical and experimental evidence that comets grow in an extremely cold, quiescent environment is proving difficult to reconcile with recent CO and IR observations showing that the environment of a star-forming region is characterised by turbulent, high-velocity flows and that young stars are prone to recurrent, violent outbursts. The aggregation among young stars of planetesimals pre-existing in molecular clouds avoids these problems. However formed, the Oort cloud is disturbed through interactions with its galactic environment. A record of these past disturbances, episodic or regular, is in principle recoverable through impact cratering and other geological signatures, and these terrestrial records therefore provide a further new constraint on the structure and evolution of the Oort cloud. The concepts of: 'dense inner cloud' or a 'solar companion star' are difficult to reconcile with the impact cratering history. The debris from the very largest comets are expected to play a dominant role in producing galactic modulations of such fundamental phenomena as the rise and fall of oceans, ice ages, geomagnetic reversals and the origin of life. A ~15 Myr galactic cycle in particular is predicted. Power spectrum analyses applied to cratering, vulcanism and geomagnetic reversal records for the last ~200 Myr reveal the presence of a 16 ± 2 Myr cycle.

Introduction

The Oort cloud has been one of the most successful concepts in cometary dynamics. For almost 40 yr, the idea of a stable, primordial cloud of comets reaching half way to the nearest stars, and gently gardened by passing stars, has been the mainstay of cometary dynamics. It is true that the idea is based on ~1 enormous extrapolation, from a few, hundred well-determined orbits to a supposed population ~10^{12} comets, and there have been suggestions from time to time that the observations really only require a few million comets to exist in highly eccentric orbits about the Sun. A system like this would be quickly dispersed, however, and the idea that (say) ~10^{7} bodies were captured into highly eccentric orbits (e > 0.9999) a few Myr ago has never gained much acceptance. It is moreover natural to think of the formation of comets as being connected in some way with the formation of planets.

Indeed part of the significance of comets is that they represent a clue, albeit a cryptic one, to the formation of planetesimals in some environment past or present. The role of planetesimals in stellar cosmogony is at present unclear: usually they are seen as by-products of star formation, but there have been suggestions from time to time that their role is a more fundamental one. In recent years, too, many new and non-classical ideas relating to the origin and dynamics of the Oort cloud have been aired (Table 1). One of these ideas, namely that comet impacts may significantly influence Earth history, has meant that questions relating to the interactions between the Oort cloud and the Galaxy have acquired an interdisciplinary significance. Oort cloud studies have thus come to bridge a gap between star formation and galactic processes at one end of the scale, and the evolution of life on Earth at the other.

In addition to these new theoretical ideas, there have been new observational advances, some at IUE or IRAS wavelengths, and there have been experimental and in situ measurements: some of these results put constraints on the conditions existing at the sites of comet formation (Table 2). The purpose of this review is to describe briefly the current status of hypotheses about the origin, structure and dynamics of the Oort cloud, putting some emphasis on the more recent work in this area. More comprehensive reviews are given by Bailey et al. (1986, 1988).

The comet forming environment

The location of the comet factory is usually taken to be the protoplanetary disc, the solar nebula beyond, or the molecular clouds. Opik (1966, 1973, 1975) placed the comet factory in the Jupiter region where gravitational ejection is most rapid. However Jupiter is such a strong perturber that for every comet placed in the Oor. cloud about 500 would be hyperbolically ejected, and Safronov (1967, 1969, 1972, 1977) proposed instead that most comets came from the Uranus-Neptune region. This is efficient but slow, since on this hypothesis one has to wait for the giant planets to accrete (~2 Gyr), comet growth itself taking ~10^6 yr (Hills 1973). However if the disc is sufficiently quiescent, dust will settle in a thin plane, gravitational instability will take over and growth will proceed rapidly. Oort cloud dynamics, based on the assumption of comet growth in a quiescent, low-mass protoplanetary disc (M ~0.1 M_s with H and He), has been developed by Fernandez (1980, 1985a) and others.

An alternative class of models places the origin of comets beyond the planetary regions. The first of these was introduced by Cameron (1962, 1973) who argued from the perspective of star formation theory. A protostellar cloud, he considered, would collapse to form a massive disc (~1 M_s) and the growth of comets would take place in this disc, beyond the orbit of Neptune. Planetesimal growth took place rapidly because of the high mass and turbulent velocities, and the Oort cloud was populated by mass loss from the early Sun during its T Tauri phase. Although the process of comet growth was described only qualitatively, Hills (1981) produced a mechanism, based on the action of differential radiation pressure, for coagulating grains into comets around the Sun during its T Tauri phase. More recently Bailey (1987) has suggested that comets might form by the coagulation of dust in wind-driven shells around young protostars.

A third class of models postulates a truly interstellar origin for comets, generated either during solar passages through nebulae (Lyttleton 1953), or by Jeans collapse of dust (McCrea 1975), simple coagulation (Yabushita 1983) or radiative driving (Flannery & Krook 1978, Napier & Humphries 1986). Other sites have been suggested but are not discussed here: protoplanetary disc, solar nebula or molecular cloud seem to be the realistic possibilities in the current state of knowledge. They are not, of course, mutually exclusive.

There is evidence that comets must have grown in an extremely quiescent environment. This follows in part from their extremely fragile and fluffy structure, as evidenced by Brownlee particles and cometary fireballs. Further from the icy grain model of d'Hendecourt et al. (1982), the presence of volatile species in comets requires low velocity impacts between colliding grains: assuming that radicals comprise 1% of the icy mantle of a grain, they have shown that grain heating (T_g > 25 K) during mutual collisions at ~40 m s^{-1} would destroy most volatile species in an irradiated mantle. It is likely too that the comet formation environment was very cold. S_2 discovered in the coma of IRAS-Araki-Alcock 1983 VII, probably as a parent molecule, has been used as a fossil thermometer by A'Heam and Feldman (1985). Grim and Greenberg (1987) have argued that aggregation time scales must be taken into account before this can be done, but nevertheless find from their experiments that
temperatures much less than 100K, perhaps as low as 30-40 K, are required for comet formation with S$_2$ preserved. Krishna Swamy and Wallis (1987) have identified S$_2$ in several other comets including those of Halley and Encke. Assuming that comets cannot be formed out to 50 AU in an environment, whether protoplanetary disc, circumstellar nebula or molecular cloud, in which the grains come together at <40 m/s$^{-1}$ and perhaps T < 40 K.

In recent years, high resolution millimetre and infrared observations of star forming regions have become available and some observational progress in the star formation problem has been made. Current models for star formation begin with the formation of a dense core in a molecular cloud, typically with a mass a few M$_{\odot}$, T=10 to 15 K, n$_{\text{H}_2}$=10$^2$-10$^3$ cm$^{-3}$. These cores are formed from the collapse occurring outwards at the speed of sound. As collapse proceeds the more distant matter, with the higher angular momentum, is unable to reach the protostar and it falls in orbits which result in the formation of an accreting, growing disc. When the protostar has reached a mass ~0.3 M$_{\odot}$ helium burning begins, and a strong stellar wind results, which cannot escape because of the still infalling material. As the infall rate declines, however, a narrow bipolar outflow of material develops, the opening angle of the wind increasing with time until eventually it extends in all directions and further infall is stopped. One then sees, a T Tauri (solar mass) star along with a dense and luminous clump of gas and dust, known as a protostellar disc. Evidently, accretion discs may still exist at this stage, but the gas is later lost and dust discs remain around the newly formed main sequence stars. T Tauri stars themselves are the source of a powerful stellar wind, of kinetic energy 10$^{47}$ ergs.

 Highlands and lowlands in the disc surface density sequence are somewhat conical and high velocity molecular outflows are such common features in young star forming regions that they are likely to be a normal part of the first ~0.1 Myr of a star's life (Schwarz 1983).

IRAS 15399A is perhaps an archetypal collapsing protostar. It is a cold (~40 K), luminous (~23 L$_{\odot}$) object discovered in the Rho Ophiuchi molecular cloud by Walker et al. (1986), and may be a protostar only a few 10$^3$ yr old. The central point source has a mass ~0.24 M$_{\odot}$. The material surrounding the source out to ~3000 AU has n$_{\text{H}_2}$<10$^0$ cm$^{-3}$, and appears to be infalling at ~1 km s$^{-1}$. There is a simultaneous bipolar outflow. This object is very quiescent by the standards of most pre-main sequence stars. Nevertheless the CS line widths indicate that the infalling material has a microturbulent velocity ~0.4 km s$^{-1}$, an order of magnitude in excess of those just permitted by the grain coagulation models. Stellar winds seem to start up at the earliest stages of star formation. These are exemplified by the young stars in OMC-1, which have outflow velocities ~100 km s$^{-1}$. IRC2 for example being at the centre of a windblown cavity whose outflow, of velocity ~100 km s$^{-1}$, is channelled by a toroidal structure. The driving force comes from within ~0.5AU of the source, in IRC2, and the flow appears to be turbulent, with cooler, massive clumps embedded within it. Whether these clumps were ejected by the stars or are independent blobs caught up in the wind is unknown. HL Tau may exemplify a later pre-main sequence stage. This is a ~1 M$_{\odot}$ star apparently viewed through the plane of a torus of gas and dust of radius ~2000 AU and mass ~0.01-0.5 M$_{\odot}$, probably in Keplerian motion. The temperatures of the gas and grains in the ring are a few 10$^6$ K and there is a 3.1$\mu$m ice absorption feature present (Cohen 1983; Beckwith and Sargent 1987). These properties persist outside those associated with the early solar nebula, but once more the presence of jets in the system reveals that it is permeated by a strong stellar wind and it is not the extreme quiescence apparently required for comet formation is met in this system.

Herbig (1977, 1983) has pointed out that FU Orionis type outbursts, involving luminosity increases of ~100 over a period of years, are a normal recurring feature of T Tauri stars (say every ~10$^4$ yr). He has argued that such outbursts would have melted mm-sized dust particles in the inner Solar System. We can apply the same type of reasoning to the ice mantles of grains. It is easily found, from the evaporation rate of water ice at different temperatures as determined by Grim and Greenberg (1987), that a single FU Ori outburst in the early Sun, of duration ~30 yr, would have evaporated the icy mantles of grains out to 200 AU. Likewise assuming 100 outbursts each of 30 yr duration over the Myr lifetime of the T Tauri Sun, one finds that comets of ~km dimensions in circular orbits would have been evaporated out to 100 AU, comets of 10 km dimensions out to 80 AU. It should be noted that relaxed orbits in a protoplanetary disc would be approximately circular. Since ices are clearly abundant in the outer Solar System, and include such volatiles as CH$_4$, one must either postulate ad hoc a dense intervening dust shield for the entire T Tauri lifetime of the early Sun (although dust coagulation would proceed more rapidly in a higher protoplanetary region), or assume that the ices were stored in large comets (>10 km), or transported elsewhere post - T Tauri.

The conclusion which seems to be emerging is that the turbulent, powerful outflows which are associated with stellar formation from its earliest stages, and the occasional violent stellar flaring, are difficult to reconcile with the quiescent, cold environment required for comet growth by grain coagulation.

Nevertheless, there is evidence that, at least around some low-mass stars, planetesimals have appeared in a disc a few 10$^6$ AU. A systematic search of IRAS sources (Aumann 1985) has revealed that a number of them are associated with known dwarf and subgiant stars. So far four of these excess IR emitters have been modelled as dusty discs, but allowing for selection effects they may be common amongst F,G and K main sequence stars (Wolstencroft and Walker 1987). The dimensions of the particles necessary to reproduce the far IR radiation are such that the Poynting Robertson effect would have rapidly removed them, and this implies a replenishing source of larger dimensions. IUE observations of metal lines in Beta Pictoris show strong variable absorption (although not necessarily attributed to the observed ~10-100 times/yr) infall of ~km-sized planetesimals (Lagrange-Henri et al. 1987); and the dust-free holes around the stars may at least speculatively be related to the clearing out of debris from an inner planetary system as evidenced in the case of the Solar System by the late heavy lunar bombardment, of duration a few 10$^8$ yr. Whether the planetesimals are cometary in nature is unknown, however.

Weissman (1984) has attributed the source of the small dust particles in the Vega or Aldebaran collisions between larger bodies; however an accreting system is presumably a sink rather than a steady source of nm sized particles; on the other hand if the discs are fragmenting, then whence came the bodies which are now breaking up? A similar problem arises with the main belt asteroid system, which is much too 'hot' kinematically to have formed by accretion in a quiescent disc (Heppenheimer 1977). In a system of colliding bodies, relaxation is attained when the energy input from mutual gravity balances that lost from mutual collisions (Safonov 1972). The energy input is dominated by the largest planetesimals and so if it is accepted that comets have grown through grain collisions <40 m s$^{-1}$, the largest ones can only have been of ~km dimensions. In fact although no final answer is possible, it seems likely that the few largest historical comets have probably been ~100 km in diameter. This would again seem to preclude an origin in a system approaching a dynamically relaxed state, such as a circumstellar disc, whether pre-main sequence or not, and including the Uranus-Neptune region.

These problems of comet growth and survival are avoided in the third class of model, but one would then require that comets are formed in the interstellar medium prior to star formation and are then pulled in by the protostar collapse phase or are captured post-main sequence (Clube & Napier 1984a, Napier 1985). The growth of planetesimals in dense molecular clouds has been suggested to account for the lack of enrichment of the interstellar medium with time, heavy elements being progressively lost in large bodies (Tinney and Cameron 1974, Greenberg 1974). The strong correlation between metal depletion and density observed in cold molecular clouds may indicate that comet growth is proceeding fairly rapidly in such regions, the dense knots presumably being precursors of star formation. The slow homologous collapse of a molecular cloud from 10$^6$ to 1 AU would cause the indigenous planetesimals to spiral in, leading to say a 1 M$_{\odot}$ protostar surrounded by ~10$^4$ comets orbiting within ~5 AU. These would mostly be absorbed into the protostar or later destroyed, but some fraction of bodies at say a few 10$^3$ AU would survive and be retained. If this admittedly
speculative picture is correct then the long growth time for planetesimals in the hazardous Uranus-Neptune region would not be necessary.

The problem of growing large bodies in the interstellar medium has usually been seen as a severe obstacle to the interstellar planetesimal concept. However the past few years have seen a revival of a suggestion made by Spitzer and Whipple in the 1940's that differential radiation pressure might force grains together in the interstellar medium. This mechanism was applied by Hills (1981) to a T Tauri star or collapsing protostar, but it has been returned to the interstellar medium whence it came by Flannery and Sonn (1983) and Napier and Humphreys (1986). The latter have argued that the dust component of molecular clouds is unstable in the presence of a radiation field. This photon drive may be enhanced by up to two powers of ten if impinging UV photons photodescribe mantle material. It was found, from application of a generalised virial theorem, that in cold (T < 200 K), dense (n \( \geq 10^3 \) cm\(^{-3} \)) regions of a molecular cloud, planetesimals of > km dimensions may coagulate out in \( <10^3 \) yr.

Schneider and Elmegreen (1979), in their catalogue of filamentary dark clouds, point out the existence of long bead-like dark clouds, comprising chains of small, discrete globules. In addition they describe filamentary structures without condensation e.g. streamers in Ophiuchus. Often these filaments have a windswept appearance or sharper edges along one side, and they are usually significantly aligned with respect to a star. Schneider and Elmegreen propose that some highly directional force might account for this. They suggest that this external force accumulates material by sweeping it first into plane-parallel layers, and the material then fragments into parallel filaments before undergoing further gravitational condensation into individual globules. All of this, of course, is on \( \sim 1 \) pc scales and not directly applicable to comet collapse, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution (of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains. Random break-up of a collapsing dust sheet or sphere yields a scale-free mass distribution of planetesimals (a power law with index \(-1.75\) to \(-1.67\)). An upper limit to the possible masses may in principle be derived by Hills (1981) to a T Tauri star or collapsing protostar, but may support the idea of radiative driving of grains.

\[ \text{Oort cloud replenishment} \]

It seems unrealistic to suppose that the Oort cloud comets were formed by accretion processes in the interstellar medium. The most likely way in which comets could be formed in the interstellar medium would be by gravitational collapse of a clump of interstellar dust. However, this process would be very inefficient. It is estimated that only about 1 in 10^6 comets would be formed in this way. Therefore, it seems unlikely that the Oort cloud comets were formed in the interstellar medium.

The long-standing problem of Oort cloud replenishment has been reconsidered in recent years by the discovery of the molecular cloud system and the realisation that this system is so dense that it is possible that the Oort cloud comets were formed in the interstellar medium. The most likely way in which comets could be formed in the interstellar medium would be by gravitational collapse of a clump of interstellar dust. However, this process would be very inefficient. It is estimated that only about 1 in 10^6 comets would be formed in this way. Therefore, it seems unlikely that the Oort cloud comets were formed in the interstellar medium.

\[ \text{Maximum binary separations after Aht (1986).} \]

The long-period comets, then, form an unstable, rapidly dissipating system, but nevertheless they may have some possible explanations of this mechanism have been suggested. Replenishment from a hypothetical dense inner cloud is one much discussed possibility. Another possibility is that the long-period comets are somehow captured from interstellar space, say during passage through dense star-forming regions. Or it may be that no replenishment is taking place and that the observed comets are simply a much-replenished remnant of an originally very massive cloud. Adopting a power law energy distribution with index \( \gamma \), various differential distributions proposed in the literature are shown in Table 3 along with the associated distributions in \( n \) and \( r \) (the quoted \( r \) distributions are only approximate). The standard Oort cloud has \( \gamma = 5/2 \). The flat distribution of energy (\( \gamma = 0 \)) due to Van Woerkom (1948), yields \( n(\alpha)d\alpha = n_\star^{\alpha - 4/2}d\alpha \) and this is seen in the simulations of Fernandez (1980), who followed the evolution of an initial ring of comets in the plane of the Sun with periellipses initially in the Uranus-Neptune region. A dense inner cloud in the sense usually adopted (e.g. Hills 1981) has \( \gamma < 0 \), an extreme value of \( \gamma = -2 \) being proposed by Bailey (1986b) in order to directly replenish the short-period comet system from a remarkably dense, small region.
The question of replenishment of the long-period comets from an inner Oort cloud was investigated by numerical simulations. These were fairly conservative, only close encounters (≤ 40 pc) being considered, and the GMC's being taken as uniform spheres, so greatly exaggerating the softness of penetrating encounters (the clumpy structures of GMC's yield dilution factors ~0.1-0.01: loc. cit.). The GMC's were taken to be the bulk properties described by Sandell et al. (1967). A transition matrix \( \mathbf{T} \) was derived, whose elements were the probabilities that a comet initially in energy state \( i \) is perturbed to state \( j \) after 4.5 Gyr. The end state \( N_j \) of the Oort cloud may then be derived for any prescribed initial distribution \( N_i \) via \( N_j = \mathbf{T} \mathbf{N} \) without further celestial mechanics.

Although these calculations are very rough a number of interesting conclusions could be drawn (see Fig. 2). First, it was confirmed that if there was indeed a primordial Oort cloud, the 'observed' region 20,000 ≤ a ≤ 30,000 AU has been depleted over Solar System history, by at least two orders of magnitude. The standard Oort cloud, with \( y = 2.5 \), is in difficulties, and if seen as a primordial remnant the initial mass of comets would have been absurdly large, supporting the earlier conclusions of Napier and Stuninicha (1982), Clube and Napier (1982) and others. Second, in addition to this depletion, the surviving cloud is strongly mixed by GMC encounters. The GMC's act to push orbits inwards as well as outwards, driving them into a tightly-bounded, relatively long-lived core of ≤0000 AU radius and enhanced density. Third, the long-period comet system can in principle be replenished by a dense inner cloud (say \( y = -1 \)), or even a Van Woerkom cloud (\( y = 0 \)) originally only a few times more massive than the present one. The mass of the original cloud must be a matter for speculation as the maximum mass of comets is not known. Assuming for example an upper limit of 10^22 gm, the mass distribution given by Hughes and Daniels (1982), and \( y = 0 \), the original cloud would have had several 10^15M_\odot. It is not obvious that a dense inner cloud exists. However constraints can be placed on the inner cloud by looking at the effects of cometary impacts on the history of the Earth.

The Oort cloud and Earth history

The unseen inner regions of the comet cloud can be studied by a Rutherford experiment, firing stars through it and observing the scattered comets, the detection apparatus in this case being the surface of the Moon and the geological record of the Earth. The impact record is highly incomplete and contaminated by a non-cometary background, but the data are nevertheless at a level where one may put real constraints on the structure, evolution and possibly even the origin of the Oort cloud. The surveys of Shoemaker and Helin in the 1970's revealed that the population of Earth-crossing (Apollo) asteroids was one or two powers of ten higher than had been realised until then. That the energy and frequency of impacts from Apollo asteroids were high enough to lend one to expect geological signatures was first pointed out by Napier and Clube (1979), who also argued that these signatures should be imposed on the Earth with a steady asteroidal background, would seem to argue against the existence of a very dense inner core, and the problem of replenishing the outer Oort cloud remains. Roughly put, if we have \( y < 0 \) there is a problem with the impact cratering record. If \( y > 0 \), there is a problem with replenishing the Oort cloud. The latter is exacerbated by the fact that the lunar cratering rate shows no signal of a secular decline over the past 3.9 Gyr (Fig. 3; Baldwin 1985). For comparison Fernandez (1980) found that under the influence of stellar and planetary perturbations, the rate of passages of comets through the planetary system varied as \( t^{-1} \) over the Gyr of his numerical simulations with a decay time ~400 Myr. A comet source in the Uranus-Neptune region was assumed. If an appreciable proportion of this past cratering is due to cometary impacts then the replenishing reservoir must be not only very massive, but also, probably, external to the Solar System. It seems more likely therefore
geochemical anomalies at KT

galactic periodicities in composition of comets: S2;
particles sequence stars
dust discs around main bipolar flows
young star-forming regions; chemistry of GMCs
detailed structure and (Hi) with random impacts
(ii) with solar companion
(iii) with random impacts or showers

Terrestrial catastrophism

(i) with galactic modulations
(ii) with solar companion modulations
(iii) with random impacts or showers

Table 1

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<td>initially controversial but now seems well established</td>
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<tr>
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<td>3-body problem; no detailed calculations available</td>
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<tr>
<td>Galactic alignments</td>
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<tr>
<td>Dense inner cloud (γ&lt;0)</td>
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<td>Terrestrial catastrophism</td>
<td>highly controversial field</td>
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<tr>
<td>(i) with galactic modulations</td>
<td>15 and 30 Myr periodicities both proposed and disputed; dominant role of giant comets</td>
</tr>
<tr>
<td>(ii) with solar companion modulations</td>
<td>severe problems with orbital stability and compatibility with cratering record</td>
</tr>
<tr>
<td>(iii) with random impacts or showers</td>
<td>not consistent with claims of periodicity in terrestrial record</td>
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Table 2

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<tr>
<td>geochemical anomalies at KT boundary and in polar ice; &quot;galactic&quot; periodicities in terrestrial phenomena</td>
<td>evidence of Oort cloud disturbances</td>
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Table 3

<table>
<thead>
<tr>
<th>Oort cloud distributions</th>
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<tr>
<td>γ = 5/2</td>
</tr>
<tr>
<td>γ = 0</td>
</tr>
<tr>
<td>γ = -1</td>
</tr>
<tr>
<td>γ = -2</td>
</tr>
<tr>
<td>nD(a)</td>
</tr>
<tr>
<td>a-1</td>
</tr>
<tr>
<td>a-2</td>
</tr>
<tr>
<td>a-3</td>
</tr>
<tr>
<td>a-4</td>
</tr>
<tr>
<td>nE(E)</td>
</tr>
<tr>
<td>E-5/2</td>
</tr>
<tr>
<td>E0</td>
</tr>
<tr>
<td>E*</td>
</tr>
<tr>
<td>E2</td>
</tr>
<tr>
<td>nF(r)</td>
</tr>
<tr>
<td>r-3/2</td>
</tr>
<tr>
<td>r-4</td>
</tr>
<tr>
<td>r-5</td>
</tr>
<tr>
<td>r-6</td>
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</table>

The notion that terrestrial processes recur cyclically is very old, and individual workers, each in their own specialization have in the past uncovered more or less qualitative evidence for it. Over 50 yr ago Holmes (1927), before the plate tectonic revolution and radiometric dating of rocks, considered that sea levels rose and fell in a 30 Myr cycle which was correlated with world-wide outbursts of volcanic activity. Dorman (1968), from a study of marine fossils, thought there was a 30 Myr world-wide climatic cycle. Seyfert and Sirkin (1979) found what they called 'impact episodes', a tendency for impact cratering to recur at ~26 Myr intervals. They correlated these episodes with plate tectonic and other phenomena. Although their approach was again qualitative and they made no attempt to discriminate between types of body, there is a good correlation between their impact episodes and those found by Alvarez and Muller (1984) by power spectrum analysis (Clube & Napier 1986). The one significant difference is that Seyfert & Sirkin find the Earth to be currently immersed in an impact episode. A ~30 Myr cycle is about the half period of the Sun's vertical motion in the Galaxy, and Clube and Napier (1984a) and Rampino and Siotieres (1984) proposed that the Oort cloud disturbances were varying systematically with this motion. The occurrence of galactic periodicities in the terrestrial record, through Oort cloud disturbances, had been predicted by Napier and Clube (1979) and Clube and Napier (1982), the possibility of 15 and 30 Myr cycles being explicitly mentioned by Napier (1983).

It has been argued by Thaddeus and Chanan (1984) that the Sun's vertical motion is too small relative to the scale height of the molecular cloud system for appreciable modulation of the comet flux to take place. However for the periodic component of the comet flux, what matters is the smoothed integrated effect of it on the number of comets, a part of which expresses itself as an increase in the vertical galactic tide. If this tide is generated by a smooth, plane-parallel continuum, then it varies linearly with the effective mass density of local perturbers. This tidal background (Byl 1986) gives a flux of near parabolic comets into the planetary system directly proportional to the local density. The comet flux therefore samples the instantaneous local density as the Sun moves up and down and, provided the 'missing mass' in the Galaxy has a half-thickness ≤60 pc say, 30 Myr periodicity in the terrestrial record will be quite measurable. The effects of galactic tides on cometary orbits & the tendency for aphelion to avoid galactic poles has been noted by Delcenne (1987).

However the spatial structure of the galactic tide, and thus the temporal variations in comet influx, are very uncertain: the vertical and horizontal distributions of the missing mass are unknown and indeed its existence has been questioned (G Gilmore pers. comm.). It may be that an appreciable fraction of the mass of the galactic disc is 'granular', being concentrated say
TABLE 4. Probable debris from the most recent giant short-period comet (after Clube & Napier 1986b, Table 3, and Oort - Steel 1988)

<table>
<thead>
<tr>
<th>Object</th>
<th>g(AU)</th>
<th>ε</th>
<th>(deg)</th>
<th>ω(deg)</th>
<th>comment</th>
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<td></td>
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<td></td>
<td></td>
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<td>1) S Taurids</td>
<td>1.93</td>
<td>.806</td>
<td>5.2</td>
<td>153.2</td>
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<td>2) N Taurids</td>
<td>2.59</td>
<td>.864</td>
<td>2.4</td>
<td>162.3</td>
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<td>3) β Taurids</td>
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<td>.85</td>
<td>6</td>
<td>162.4</td>
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<tr>
<td>4) γ Pencids</td>
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<td>.79</td>
<td>0</td>
<td>13</td>
<td></td>
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<td>5) S Piscids</td>
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<td>7) S \ Orionids</td>
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<td>8) N \ Orionids</td>
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<td>11.9</td>
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<td>10) Rudnichi</td>
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<td>1.00</td>
<td>9.1</td>
<td>154.7</td>
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<td>asteroids</td>
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<td>2.2</td>
<td>.71</td>
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<td>16) unseen companion</td>
<td>2.4</td>
<td>.86</td>
<td>-</td>
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<td>impactors</td>
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<td>17) boulder flux</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18) boulder swarm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19) Tunguska object</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>20) Bruno object</td>
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<td>larger complexes</td>
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<td>21) Stohl streams</td>
<td></td>
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<td>22) zodiacal cloud</td>
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in molecular clouds which are themselves probably concentrated in spiral arms. This would yield a tensile tidal force which, about a molecular cloud scale height, partially offsets the compressive tide due to the smoothed component of the disc (Fig 4). The 30 Myr modulation itself be itself modulated, the end result being a ~15 Myr cycle with weak and strong phases interspersing. In a very incomplete record the 15 Myr component could be missed and a 30 Myr one derived. However the 15 Myr cycle is a uniquely galactic signature which discriminates this hypothesis from all others, such as random impact (Alvarez et al. 1980) solar companion (Davis et al. 1984) and so on.

In Figs. 5-7 are shown power spectrum analyses applied to various terrestrial data for the past ~200 Myr. All of these terrestrial phenomena are expected to be modulated by galactic disturbances of the Oort cloud (Clube and Napier 1982). Peaks are evident at the expected locations, within the errors, the 16±2 Myr cycles having confidence levels ~99% if they are regarded as a priori predictions of the galactic hypothesis (Clube and Napier, 1987). The geomagnetic reversal record is shown explicitly in Fig. 8, where a weak 'interpulse' is marked against the larger ~30 Myr cycle.

If these terrestrial cycles are truly galactic in origin, then the 'Rutherford experiment' as recorded in the terrestrial and lunar cratering records uniquely constrains the unseen structure of the Oort cloud. In particular the long-term steadiness of the lunar cratering then implies the existence of a huge comet reservoir; but if in the Solar System, it is difficult to see how this reservoir was formed or how it could escape detection through the generation of strong impact episodes.

![Figure 3](image-url)  
Lunar cratering record after Baldwin (1985)
Fig. 4 Smooth (a) and granular (b) tidal forces.

Fig. 7 PSA of Indian volcanisms from Pandey and Negi (1987).

Fig. 8 Geomagnetic reversal record after Harland et al. (1982). A strong ~30 Myr period (peaks joined by solid lines) appears to be interspersed with weaker 'interpulses', marked by arrows.

Conclusion

Comet cosmogony is a fashion-prone field of astronomy and its literature is strewn with the corpses of solar companions, dense inner clouds and abandoned consensus. The emergence of new observational data, such as those provided by the cratering record and protostellar environments, may help to constrain the myriad theoretical possibilities. Some of the popular ideas of the last ~30 yr already seem to be in difficulty.

Acknowledgement

The author is indebted to Mrs Anne Bryans for her typing efforts, and to Dr. M.E. Bailey for a detailed critique.
REFERENCES

Byl, J.: 1985, Earth, Moon and Planets 36, 263.

DISCUSSION

Shulman: Do you think that the density 10^5 to 10^6 cm^-3 is good enough to make comets in the appropriate time?
Napier: Yes. The mechanism is similar to that proposed by Spitzer. The outer radiation forces the gas condensation.
1. INTRODUCTION

The idea of the existence of a large reservoir of comets surrounding the Sun at a mean distance of 50,000 AU was proposed by J. Oort in 1950. Since then many authors have investigated, both theoretically and by means of numerical experiments, the origin, dynamical properties and lifetime of such a cloud, as well as the interactions that it would have with the extra-solar, galactic environment (Bailey, 1983; Bailey et al., 1984; Cameron, 1973; Clube and Napier, 1984; Delsenne, 1985; Fernández, 1980, 1982, 1985; Fernández and Ip, 1981; Hills, 1981; Lyttleton, 1974; Marsden and Sekanina, 1973; Mignard and Remy, 1985; Napier and Stanisic, 1982; Opik, 1973; Remy and Mignard, 1985; Safronov, 1969; Valtonen, 1983; Valtonen and Inmanen, 1982; Weissman, 1982, 1985; Yabushita, 1979).

Data coming from the Infrared Astronomical Satellite (IRAS) have recently shown that several stars, not far from the Sun, are embedded in a cloud of objects radiating at infrared wavelengths, and it has been proposed that these may be clouds of "comets" similar to the one supposed to exist around the Sun (Weissman, 1984).

The structure and properties of the Oort cloud have been reviewed many times (see, for example, Fernández, 1985; Weissman, 1985, and references therein contained); here we will only give a short account of what are thought to be the possible dynamical channels connecting objects in the cloud to the observed, highly structured population of short-period comets.

The possible end-states of the dynamical processes that transfer comets from the cloud to the inner solar system are reviewed in the next Section, together with the single-stage and multi-stage capture mechanisms. In Section 3 we will examine the population of short-period (SP) comets in detail, looking for differences and similarities from a dynamical point of view.

Close planetary encounters and temporary satellite captures are treated in Section 4, and librating motions around resonances with the major planets in Section 5. Since the dynamical evolution of SP comets has been the subject of many numerical experiments in the last twenty years, in Section 6 the integration of motions of observed comets and the results of Monte Carlo investigations are compared, in order to get information about the frequency of different dynamical processes.

2. FROM LONG-PERIOD TO SHORT-PERIOD COMETS

The formation of the Oort cloud is currently considered as a by-product of the accumulation of giant planets, especially Uranus and Neptune. These planets, at a late stage of their formation, should have expelled a large number of planetesimals (the present comets), with velocities close to the escape velocity from the solar system. The orbits of the small fraction of comets that remained bound to our star would have been randomized, both in eccentricity and orientation, by the perturbations originated by repeated passages of other stars in the vicinity of the Sun. The result of this process would have been a more or less uniform distribution of orbits with mean semi-axes of the order of 25,000 AU, and perihelion distances well beyond the planetary region. If no perturbations from objects outside the solar system were present, this situation would be stable over very long time spans, greater than the age of the system itself, because encounters and collisions between comets in the cloud are thought to be irrelevant for the evolution of that population.

Four possible sources of perturbations on the comet's cloud have been proposed in recent years. Passing stars, of course, would induce orbital variations, almost impulsive in nature, on a small fraction of objects on the same side of the star, with respect to the Sun; the size of these perturbations would then depend mainly on the minimum distance of the star from the Sun and on its relative velocity. A second source of perturbations comes from the observation that the solar system must have encountered several times, in the past, giant molecular clouds (Clube, 1985). The great masses of these objects would have caused large losses of comets from the cloud, especially at large distances from the Sun; they may have even completely depopulated the cloud. A third source, that has been invoked to justify the idea of periodic cometary showers on Earth, could be the presence, at a large distan-
ce from the Sun, of a very massive planet, or even a second star (Withmire and Jackson, 1984), whose period has been estimated to be of the order of 20 to 30 million years. Finally, Harrington (1985) has shown that galactic perturbations may be able to randomize cometary orbits in the Oort cloud.

Whatever the sources of external perturbations, it almost invariably turns out that the effects on the cloud of comets is smaller or at most comparable to that due to passing stars. For what concerns the transfer of a comet into a SP orbit, we will then start with an orbit of very long period, entering the planetary region for the first time after its removal into the Oort cloud. Such a comet, revolving on a quasi-parabolic orbit, is called a new comet (in the Oort sense). Conventionally, a comet is considered new if the reciprocal of its semiaxis at a great distance from the planetary region, 1/a, is between 1/100,000 and 1/25,000 AU−1.

The subsequent evolution of a new comet, as shown by the numerical experiments by Everhart (1977), is closely related to the inclination to the ecliptic and the perihelion distance of its orbit. In fig. 1 is presented a scheme, due to Everhart (1982), of the possible end-states of the process of extraction of a comet from the Oort cloud, that will represent the start point for the following considerations.

![Evolutionary channels connecting parabolic to short-period comets](image)

The most important character of the orbit of a new comet is its possibility to cross the orbits of major planets, which can produce, sooner or later, a close encounter with them. Formally, this is possible if the perihelion distance of the cometary orbit is less than the semiaxis of those planets, but the real possibility of an encounter is limited by the mutual inclination of the orbits and the orientations of the lines of nodes and apses. If the angles are in a suitable range, and then a close encounter may take place, the evolution of the comet's orbit is mainly governed by the relative speed at encounter (U) which, in turn, is related to the so-called Tisserand quantity, J, by the equations:

\[ U = \sqrt{3 - J} \]

\[ J = a_p/a + 2\sqrt{a/a_p (1-e^2)} \cos i \]

where U is measured in units of the planet's orbital velocity, a, e, i are the semiaxis, eccentricity and inclination of the comet's orbit and a_p is the semi-axis of the planet.

The Tisserand quantity, a simplification of the Jacobi constant of the restricted three-body problem, has the property of remaining almost constant after an encounter, although its value during the encounter may change substantially. Due to the ease of computation from the parameters of an osculating orbit, the Tisserand quantity has been used in the past to identify a comet whose orbit was changed by an encounter with some major planet, taking advantage of the mentioned quasi-invariance. Following Kresák (1972), we will make use of this quantity in the following, as an orbital indicator.

It should not be frequent that a new comet encounters a planet during its first revolution; instead, it will perform a number of them before such an event, and may even be expelled from the system without encountering any planet. This is due to the fact that, outside the planetary region, the comet moves along an orbit whose centre of motion is the barycentre of the solar system. As the comet approaches the Sun, and crosses the orbits of the outer planets, the centre of motion is shifted, producing an indirect perturbation on the orbit. Only inside the orbit of Jupiter the comet may be supposed to move along a heliocentric orbit (due to the little mass of the inner planets), and the shift of the centre of motion repeats as the object recedes from the Sun. These indirect perturbations (see Carusi et al., 1986, 1987) may be sufficient to provide the small amount of energy needed to transform the new, quasi-parabolic orbit into an hyperbolic orbit, so that the comet will be lost in the interstellar space.

Before a close encounter takes place, the orbit of the comet may undergo several changes, due to the above mechanism, and become an old comet of long period; the same may happen if the comet encounters some planet at a relatively large distance. If the encounter is close, however, the comet may still be put into a hyperbolic orbit, and then escape from the system (like in the recent case of comet Bowell), or its orbital period may be shortened considerably.

It is relevant, at this point, a consideration on the values of the Tisserand quantity with respect to the major planets. It has been shown (see, for example, Carusi and Valsecchi, 1985) that the dynamical evolution of a comet differs considerably if J is less than 2, or greater than that. Comets with low, or very low, values of J have a high relative velocity at encounters, and their orbits will not be changed by a large amount, unless the encounter is extremely close. In this last case, either the comet is put into a hyperbolic orbit, or is definitely trapped in the planetary region. Considering the masses of the planets, and the probability of a passage at a given distance from them, it turns out that Jupiter is the major source of this
type of orbit transformations (single-stage captures): its gravitational field is, in fact, able to produce - in a single encounter - a SP comet. As an example of this phenomenon (although reversed in time), fig. 2 shows the consequences of a very deep encounter of P/Lexell with Jupiter, in 1779; the comet has been put into a very elongated ellipse. In fact, a small difference in the timing of the event would have produced a parabolic comet (Carusi et al., 1982). It has been proposed (Everhart, 1977; Carusi et al., 1986) that SP comets with \( J \leq 2 \) were captured by Jupiter in this way; a representative of this group of SP comets is P/Halley.

The situation is considerably different when \( J \) is greater, or much greater, than 2, although this value must be considered as purely conventional. These comets, as a matter of fact, have low relative velocities at encounters, and may exhibit a number of dynamical phenomena, such as temporary satellite captures or temporary librations. These comets, through successive encounters with the giant planets, can be gradually transferred from Neptune, to Uranus, to Saturn and finally to Jupiter. Some steps may, of course, be jumped, and at any point the comet can reverse its inward trend, under suitable conditions; anyway, one of the end states of this evolution is an orbit in the so-called Jupiter family. Owing to the succession of interactions with several planets, each of them requiring at least a close encounter, this process has been called multi-stage capture. It is thought that the majority of SP comets was originated in this way.

3. DIFFERENT TYPES OF SHORT-PERIOD COMETS

Some 140 SP comets have been observed so far. Many of them have revolution periods such that a second passage close to the Sun, since the time of discovery, has not yet taken place: they are the one-apparition comets. Among these, however, are comets that should have been observed more than once and the absence of their recovery may be due either to poor knowledge of their orbits, or to a definitive extinction as active objects, or to a major change in the orbital elements due to a close encounter with a planet (mainly Jupiter). More than 80 SP comets have been observed several times (P/Halley has been under observation for 22 centuries).

We have already noted that not all SP comets have the same dynamical characters, nor the same dynamical origin. It may be of interest to analyze their orbits in some detail, in order to elucidate the internal structure of this dynamically important population of minor bodies. This analysis is now facilitated by the existence of long-term integrations of comet's motions (Belyaev et al., 1986; Carusi et al., 1985), the longest of which covers a time span (821 years) comparable with the supposed lifetime of comets as active objects.

A first subgroup already mentioned, consists of the comets with \( J < 2 \). We will call them Halley-type (HT) comets (table I), although this designation has been used in the past with a somewhat different definition. We have said that these comets have probably been transferred to orbits of short period as a consequence of a single encounter with Jupiter. Moreover, as shown in Carusi et al. (1986), their dynamical characteristics are so closely resembling those of comets with longer periods (between 200 and 1000 years) that it seems natural to conclude that Halley-type comets are the "tail" of long-period comets towards short orbital periods.

On the other extreme of \( J \), close to 3 and on both sides of this value, there is a group of comets characterized by having their orbits nearly tangential to that of Jupiter either in their perihelion or aphelion. P/Oterma and P/Gehrels 3 are nice examples of this peculiar group; their main dynamical feature is a very low velocity relative to Jupiter, which cause rather frequent, deep and efficient encounters with drastic changes of the orbital elements. Due to the low encounter velocity, the osculating orbital parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>( J )</th>
<th>a</th>
<th>e</th>
<th>i</th>
</tr>
</thead>
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<tr>
<td>P/Tempel-Tuttle</td>
<td>-0.64</td>
<td>10.27</td>
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</tr>
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<tr>
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<td>85.11</td>
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<td>11.25</td>
<td>0.860</td>
<td>17.98</td>
</tr>
</tbody>
</table>
with respect to Jupiter become often elliptic, leading to temporary satellite captures. Some comets of this type are listed in table II, all of them with \( 2.9 < J < 3.04 \). Another interesting feature of these orbits is represented by the rather frequent exchanges of perihelion with aphelion, as a consequence of an encounter, that is a clear signature of their stepwise capture from a long-period orbit. P/Oterma is the only comet for which the transfer of dynamical control from Saturn to Jupiter, that took place rather recently, has been reconstructed numerically (see fig. 3).

![Fig. 3 - Orbits of P/Oterma in 1770 (a), 1933 (b), 1960 (c) and 1967 (d). Between (a) and (b) there have been 1 encounter with Saturn and 2 with Jupiter. (c) and (d) are preceded by close encounters with Jupiter.](image)

Table II. Comets with high-J orbits, often undergoing temporary satellite captures during close encounters.

<table>
<thead>
<tr>
<th>Name</th>
<th>( J )</th>
<th>( a )</th>
<th>( e )</th>
<th>( I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Schwassmann-Wachmann 2</td>
<td>3.00</td>
<td>3.48</td>
<td>0.387</td>
<td>3.73</td>
</tr>
<tr>
<td>P/Whipple</td>
<td>2.94</td>
<td>3.82</td>
<td>0.353</td>
<td>10.24</td>
</tr>
<tr>
<td>P/Oterma</td>
<td>3.04</td>
<td>3.96</td>
<td>0.144</td>
<td>3.99</td>
</tr>
<tr>
<td>P/Gunn</td>
<td>3.00</td>
<td>3.59</td>
<td>0.319</td>
<td>10.38</td>
</tr>
<tr>
<td>P/Shajn-Schaldach</td>
<td>2.93</td>
<td>3.75</td>
<td>0.406</td>
<td>6.15</td>
</tr>
<tr>
<td>P/Smirnova-Chernykh</td>
<td>3.01</td>
<td>4.17</td>
<td>0.145</td>
<td>6.64</td>
</tr>
<tr>
<td>P/Gehrels 3</td>
<td>3.03</td>
<td>4.04</td>
<td>0.152</td>
<td>1.10</td>
</tr>
<tr>
<td>P/Wild 3</td>
<td>2.93</td>
<td>3.62</td>
<td>0.368</td>
<td>15.66</td>
</tr>
<tr>
<td>P/Bus</td>
<td>3.01</td>
<td>3.49</td>
<td>0.375</td>
<td>2.58</td>
</tr>
<tr>
<td>P/Russell 3</td>
<td>2.92</td>
<td>3.82</td>
<td>0.344</td>
<td>14.10</td>
</tr>
<tr>
<td>P/Russell 4</td>
<td>3.00</td>
<td>3.45</td>
<td>0.383</td>
<td>6.25</td>
</tr>
</tbody>
</table>

Table III. Comets with orbits between Jupiter and Saturn.

<table>
<thead>
<tr>
<th>Name</th>
<th>( J )</th>
<th>( a )</th>
<th>( e )</th>
<th>( I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Schwassmann-Wachmann 1</td>
<td>2.98</td>
<td>6.09</td>
<td>0.105</td>
<td>9.75</td>
</tr>
<tr>
<td>P/Neujmin 1</td>
<td>2.16</td>
<td>6.85</td>
<td>0.775</td>
<td>15.03</td>
</tr>
<tr>
<td>P/Van Biesbroeck</td>
<td>2.65</td>
<td>5.36</td>
<td>0.550</td>
<td>6.60</td>
</tr>
<tr>
<td>P/Wild 1</td>
<td>2.42</td>
<td>5.61</td>
<td>0.647</td>
<td>19.89</td>
</tr>
<tr>
<td>P/Fd Toit</td>
<td>2.12</td>
<td>6.07</td>
<td>0.787</td>
<td>18.70</td>
</tr>
<tr>
<td>P/Sangun</td>
<td>2.41</td>
<td>5.39</td>
<td>0.664</td>
<td>18.64</td>
</tr>
<tr>
<td>P/Gehrels 1</td>
<td>2.89</td>
<td>5.95</td>
<td>0.597</td>
<td>9.64</td>
</tr>
<tr>
<td>P/Kowal 1</td>
<td>2.95</td>
<td>6.11</td>
<td>0.237</td>
<td>4.36</td>
</tr>
<tr>
<td>P/van Houten</td>
<td>2.86</td>
<td>6.25</td>
<td>0.367</td>
<td>6.65</td>
</tr>
<tr>
<td>P/Chernykh</td>
<td>2.59</td>
<td>6.33</td>
<td>0.594</td>
<td>5.73</td>
</tr>
<tr>
<td>P/Bowell-Skiff</td>
<td>2.42</td>
<td>6.26</td>
<td>0.689</td>
<td>3.79</td>
</tr>
<tr>
<td>P/IRAS</td>
<td>1.96</td>
<td>5.58</td>
<td>0.696</td>
<td>46.18</td>
</tr>
<tr>
<td>P/Kowal-Vavrová</td>
<td>2.60</td>
<td>6.34</td>
<td>0.588</td>
<td>4.32</td>
</tr>
</tbody>
</table>

4. CLOSE ENCOUNTERS AND SATELLITE CAPTURES

The possibility of close encounters is obviously tied to the orientation and size of cometary orbits. Among the known SP comets there are cases (like P/IRAS, for example) of comets which cannot encounter Jupiter, due to the high inclination and the unfavourable alignment of nodes. Other comets, like those of Halley-type, only seldom pass close to a planet, since their orbital periods are longer than those of other comets of short period, and their low values of \( J \) would allow only very fast encounters, anyway. An exceptional comet is P/Encke, whose aphelion distance, 4.1 AU, is the smallest of all SP comets. Since the perihelion distance of Jupiter is 4.95 AU, P/Encke is never close to the planet, their relative distance being 0.85 AU at least.

Computer experiments (see for example Carusi and Pozzi, 1978; Carusi et al., 1979) show that the values of the "sphere of action," frequently encountered in literature, have little meaning and are of little help especially in cases in which the encounter velocity is low or very low. As a matter of fact, the efficiency of an encounter in varying the orbital elements of a comet strongly depends on the value of the Tisserand quantity and, of course, on the minimum distance of approach. We have already seen how a single encounter with Jupiter is sufficient to transform a very long period comet in a SP comet, or of changing a perihelion-tangent orbit into an aphelion-tangent one. The last process, rather common among high-J comets, is responsible for most cases of multi-stage capture; it shows also the great instability of chaotic orbits.

The frequency of close encounters differs widely from case to case. The probability per revolution of a specific behaviours, presumably all temporary in nature.
passage within a given distance from a planet increases with J, as well as the "efficiency" of the encounter in varying the orbital elements of the comet. However this is not a strict rule; we have already seen that P/Encke, the comet with the highest value of J, cannot in fact encounter Jupiter at all, its aphelion distance being decoupled from the orbit of the planet. In the long-term integration by Carusi et al. (1985) (that contains the most extended sample of encounters occurred to observed comets) there are objects that did not encounter any planet over a time span of 821 years (table IV). Many of them (18 out of 27) are HT comets.

Table IV. Comets with no encounters with the major planets (within 0.5 AU) in the period 1585-2406.

<table>
<thead>
<tr>
<th>Name</th>
<th>Relevant orbital features</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Encke</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Tuttle</td>
<td>Low aphelion distance</td>
</tr>
<tr>
<td>P/Crommelin</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Tempest 2</td>
<td>1/2 resonance</td>
</tr>
<tr>
<td>P/Pons-Brooks</td>
<td>Halley-type, also 6/1 resonance</td>
</tr>
<tr>
<td>P/Olbers</td>
<td>Halley-type, also 6/1 resonance</td>
</tr>
<tr>
<td>P/Westphal</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Brorsen-Metcalf</td>
<td>Halley-type, also 6/1 resonance</td>
</tr>
<tr>
<td>P/Schwassmann-Wachmann 1</td>
<td>High aphelion distance, Between Jupiter and Saturn also 3/2 resonance</td>
</tr>
<tr>
<td>P/Neujmin 1</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Herschel-Rigollet</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Stephen-Oterma</td>
<td>Halley-type, 2/3 resonance</td>
</tr>
<tr>
<td>P/Arend</td>
<td>Between Jupiter and Saturn also 5/4 resonance</td>
</tr>
<tr>
<td>P/du Toit</td>
<td>2/3 resonance</td>
</tr>
<tr>
<td>P/Peters-Hartley</td>
<td>2/3 resonance</td>
</tr>
<tr>
<td>P/Pigott</td>
<td>1/2 resonance</td>
</tr>
<tr>
<td>P/Pons-Gambart</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/de Vico</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Swift-Tuttle</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Barnard 2</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Mellish</td>
<td>Halley-type, also 5/1 resonance</td>
</tr>
<tr>
<td>P/Dubiago</td>
<td>Halley-type, Halley-type, also 5/1 resonance</td>
</tr>
<tr>
<td>P/Brink</td>
<td>Halley-type</td>
</tr>
<tr>
<td>P/Gehrels 2</td>
<td>Halley-type, also 5/1 resonance</td>
</tr>
<tr>
<td>P/Bradfield</td>
<td>Halley-type</td>
</tr>
</tbody>
</table>

Table V. Comets which undergo more than 0.1 encounters per revolution within 0.5 AU from the major planets.

<table>
<thead>
<tr>
<th>Name</th>
<th>J</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/d'Arrest</td>
<td>2.71</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Pons-Winnecke</td>
<td>2.68</td>
<td>irregular</td>
</tr>
<tr>
<td>P/Finlay</td>
<td>2.62</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Neujmin 2</td>
<td>2.90</td>
<td>chaotic, extinct?</td>
</tr>
<tr>
<td>P/Wolf-Harrington</td>
<td>2.81</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Honda-Mrkos-Pajdušákova</td>
<td>2.60</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Churyumov-Gerasimenko</td>
<td>2.75</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Schwassmann-Wachmann 3</td>
<td>2.77</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Kohoutek</td>
<td>2.89</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Smirnova-Chernykh</td>
<td>3.00</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Helfensteinrider</td>
<td>2.67</td>
<td>chaotic, lost</td>
</tr>
<tr>
<td>P/Lexell</td>
<td>2.73</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Kowal 2</td>
<td>2.78</td>
<td>chaotic</td>
</tr>
<tr>
<td>P/Bus</td>
<td>2.98</td>
<td>chaotic</td>
</tr>
</tbody>
</table>

Two comets (P/IRAS and P/Hartley-IRAS) with J < 2 have encounters with Saturn and Jupiter, respectively. Both orbits are of high inclination (45 degrees for P/IRAS and more than 90 for P/Hartley-IRAS) and then their encounters are not very effective. While P/IRAS cannot encounter Jupiter in the present orbit, because of the unfavourable orientation of it, the opposite is true for the other comet, thus showing the importance of the orientation in space of the two orbits (that of the planet and especially that of the comet) in preventing close encounters for a relatively long time, at least until the rotation of the line of nodes and of the line of apses may allow a close encounter. At the same time, shallow approaches to Saturn may cause a more or less pronounced variation of the Tisserand quantity with respect to Jupiter; in the case of P/IRAS it has been shown that this quantity was greater than 2 in the past, before a close approach to Saturn in 1950 (Carusi et al., 1985).

On the other extreme, the comets that undergo the maximum number of encounters (greater than 0.1 per revolution) have their values of J greater than 2.6 (see table V); all of them have chaotic orbits, often wandering between the 1/2 and 2/3 resonances with Jupiter and sometimes displaying just one cycle of temporary libration about the first of these resonances. P/Pons-Winnecke is the only comet of this group which exhibit a persisting libration, that is very irregular, however. A peculiar case is represented by P/Lexell, with three encounters with Jupiter before the injection into an orbit with period of more than 280 years; the number of encounters per revolution in this case is high, because the number of revolutions is very small in the time span considered.

For what concerns the "efficiency" of the encounters, one may compute the absolute value of the cumulative relative variations in orbital energy, \(|\Delta E/E|\). The minimum of this quantity is given by P/Encke (0.24) and the maximum by P/Gehrels 3 (7.41); it is worth noting that these two comets have some of the highest values of J: 3.025 and 3.016 respectively (only P/Oterma has a J-value greater than those: 3.04). With the except-
ion of P/Encke, however, the less disturbed orbits have $J < 2.6$ (sometimes less than 2.2) and the most disturbed ones have $J > 2.7$ (often > 2.9, see table VI). It is natural to conclude that the size of the total perturbations on a cometary orbit is also strongly dependent on the value of $J$, even on rather long time spans including several close encounters.

Temporary satellite captures are a rather frequent event among comets on high-$J$ orbits. In fact, among the 17 well determined events of this type found by Carusi et al. (1985) relative to 9 comets, 12 are due to only 4 objects: P/Gehrels 3 (5 captures), P/Schwassmann-Wachmann 2 (3 captures), P/Oterma and P/Smirnova-Chernykh (2 captures each, see table VII). Of the remaining 5 events, 3 occur on orbits of still high $J$: P/Gunn, P/Shajn-Schaldach, P/Bus, and only two with rather "low" values of $J$: P/Russell 3 and P/Giclas.

Table VI. Orbital perturbations over 821 years. The quantity $S|\Delta E/E|$ is computed summing up the absolute values of relative energy variations every 800 days.

<table>
<thead>
<tr>
<th>$&lt;0.4$</th>
<th>$&lt;0.5$</th>
<th>$&gt;2.0$</th>
<th>$&gt;4.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Encke</td>
<td>P/Borrelly</td>
<td>P/Brooks 2</td>
<td>P/Kearns-Kwee</td>
</tr>
<tr>
<td>P/Tuttle</td>
<td>P/Wild 1</td>
<td>P/Gunn</td>
<td>P/Smirnova-Chernykh</td>
</tr>
<tr>
<td>P/Peters-Hartley</td>
<td>P/du Toit</td>
<td>P/Lexell</td>
<td>P/Gehrels 3</td>
</tr>
<tr>
<td>P/IRAS</td>
<td>P/Pigott</td>
<td>P/Whipple</td>
<td>P/Wild 2</td>
</tr>
<tr>
<td>P/Brooks 1</td>
<td>P/Oterma</td>
<td>P/Oterma</td>
<td>P/Gehrels 3</td>
</tr>
<tr>
<td>P/Wild 3</td>
<td>P/Wolf-Harrington</td>
<td>P/Ashbrook-Jackson</td>
<td></td>
</tr>
<tr>
<td>P/Shajn-Schaldach</td>
<td>P/West-Kohoutek-Ikemura</td>
<td>P/Gehrels 2</td>
<td></td>
</tr>
<tr>
<td>P/Smirnova-Chernykh</td>
<td>P/Gehrels-Wachmann 2</td>
<td>P/Schwassmann-Wachmann 2</td>
<td></td>
</tr>
<tr>
<td>P/Smirnova-Chernykh</td>
<td>P/Bus</td>
<td>P/Russell 3</td>
<td></td>
</tr>
</tbody>
</table>

Table VII. Temporary satellite captures.

<table>
<thead>
<tr>
<th>Name</th>
<th>J</th>
<th>Epoch of min. dist.</th>
<th>Duration (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Schwassmann-Wachmann 2</td>
<td>2.97</td>
<td>1665</td>
<td>6.59</td>
</tr>
<tr>
<td>P/Schwassmann-Wachmann 2</td>
<td>2.98</td>
<td>1926</td>
<td>1.40</td>
</tr>
<tr>
<td>P/Schwassmann-Wachmann 2</td>
<td>3.00</td>
<td>1997</td>
<td>0.99</td>
</tr>
<tr>
<td>P/Oterma</td>
<td>3.02</td>
<td>1937</td>
<td>4.07</td>
</tr>
<tr>
<td>P/Oterma</td>
<td>3.03</td>
<td>1963</td>
<td>3.32</td>
</tr>
<tr>
<td>P/Gunn</td>
<td>2.99</td>
<td>1872</td>
<td>5.45</td>
</tr>
<tr>
<td>P/Shajn-Schaldach</td>
<td>2.96</td>
<td>1946</td>
<td>1.53</td>
</tr>
<tr>
<td>P/Smirnova-Chernykh</td>
<td>3.01</td>
<td>2030</td>
<td>5.80</td>
</tr>
<tr>
<td>P/Smirnova-Chernykh</td>
<td>2.99</td>
<td>2077</td>
<td>2.16</td>
</tr>
<tr>
<td>P/Gehrels 3</td>
<td>3.00</td>
<td>1970</td>
<td>7.50</td>
</tr>
<tr>
<td>P/Gehrels 3</td>
<td>3.02</td>
<td>2062</td>
<td>9.77</td>
</tr>
<tr>
<td>P/Gehrels 3</td>
<td>3.02</td>
<td>2203</td>
<td>4.56</td>
</tr>
<tr>
<td>P/Gehrels 3</td>
<td>2.99</td>
<td>2305</td>
<td>4.46</td>
</tr>
<tr>
<td>P/Gehrels 3</td>
<td>3.02</td>
<td>2400</td>
<td>5.22</td>
</tr>
<tr>
<td>P/Giclas</td>
<td>2.88</td>
<td>2308</td>
<td>1.38</td>
</tr>
<tr>
<td>P/Bus</td>
<td>3.01</td>
<td>2023</td>
<td>0.58</td>
</tr>
<tr>
<td>P/Russell 3</td>
<td>2.89</td>
<td>1941</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Fig. 4 - Jovicentric rotating pattern of P/Bus close to Jupiter in 2021-2028. The comet does not loop around the planet, and the satellite capture is very short.

Fig. 5 - Jovicentric rotating pattern of P/Gehrels 3 a-round Jupiter in 1963-1976. The satellite capture has lasted for more than seven years.

5. RESONANT MOTIONS

It is known since a long time that many comets of the so-called Jupiter family librate around low-order resonances with Jupiter's motion. Furthermore, there are comets which have exhibited in the past horseshoe patterns in the jovian rotating frame, and others -
with semiaxes greater than that of this planet - who librate around resonances with Jupiter that are very close to resonances with Saturn, too. More recently (see Carusi et al., 1986, 1987), it has been shown that HT comets may librate around high-order resonances with Jupiter, of the form n:1.

Basing on the mentioned long-term integrations by Carusi et al. (1985), and including the findings about HT comets, it appears that 48 out of 132 SP comets discovered up to the end of 1984 perform at least a temporary libration with Jupiter (see Table VIII). This high value (36% of the total) indicates that this process is very common among SP comets. 20 comets librate for more than 400 years, and a minority of them for at least 800 years. In one case (P/du Toit-Vico-Swift) the comet has two temporary librations around two different resonances, namely the 1/2 and the 2/3. The first of these resonances is by far the most populated, with 17 comets, followed by the 2/3 (10) and the 3/4, 1/1, 6/1 (three comets each). In the case of 1/1, however, there are two comets (P/Whipple and P/Russell) who move temporarily in a horseshoe fashion, of the type described by Everhart (1973).

The injection into, and ejection from, a temporary libration is a process that needs further study; now we can only say that it seems rather probable that a comet of the Jupiter family enters this regime of motion for a fraction of its active lifetime, thus lengthening its residence in the inner regions of solar system. This could accelerate its physical aging, since many of the objects in these orbits have rather small perihelion distances.

Table VIII. Librations around resonances with Jupiter.

<table>
<thead>
<tr>
<th>Name Res Name Res</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Churyumov-Gerasimenko 1/2</td>
</tr>
<tr>
<td>P/Clark 1/2</td>
</tr>
<tr>
<td>P/Kohoutek 1/2</td>
</tr>
<tr>
<td>P/Harrington-Wilson 1/2</td>
</tr>
<tr>
<td>P/Heinmuth 1/2</td>
</tr>
<tr>
<td>P/Holmes 1/2</td>
</tr>
<tr>
<td>P/Faye 1/2</td>
</tr>
<tr>
<td>P/Schwassmann-Wachmann 1/2</td>
</tr>
<tr>
<td>P/Asbrook-Jackson 1/2</td>
</tr>
<tr>
<td>P/Peters-Hartley 1/2</td>
</tr>
<tr>
<td>P/Wild 3 1/2</td>
</tr>
<tr>
<td>P/Viisäliä 1 1/2</td>
</tr>
<tr>
<td>P/Lovas 1/2</td>
</tr>
<tr>
<td>P/Whipple 1/2</td>
</tr>
<tr>
<td>P/Russell 1/2</td>
</tr>
<tr>
<td>P/Heinmuth 1/2</td>
</tr>
<tr>
<td>P/Arend 1/2</td>
</tr>
<tr>
<td>P/Viisäliä 2 1/2</td>
</tr>
</tbody>
</table>

The rapid development of computing tools, both hardware and software, has allowed in the last twenty years a number of numerical investigations on the dynamics of SP comets. We will briefly review the most important of them, comparing their findings with the results of long-term integrations of motion of observed comets.

These researches may be divided in two groups: in some cases the motion of individual "comets", under the gravitational influence of the Sun and some major planets, has been followed over a great number of revolutions, in order to examine the general behaviour of bodies on cometary orbits. In other cases many objects have been examined over short time spans, to provide a good statistical sample related to specific phenomena. The long-term integration of real cometary orbits may be thought of as a compromise between these two strategies, providing both evolutionary tracks over substantial periods of time and samples of dynamical phenomena relevant to the dynamics of these objects.

The process of multi-stage capture of long-period into short-period orbits has been modelled by Everhart (1977), who found a rather low efficiency in capturing comets well inside the planetary region; the majority of comets would in fact be ejected into hyperbolic orbits. However, once trapped between the orbits of Saturn and Jupiter, comets start to move on highly chaotic orbits (Everhart, 1973), which display very different regimes of motion including temporary librations, temporary and generalized trojan and horse-orbit, temporary satellite captures. As we have seen, this is exactly what happens to observed comets, a minority of which is on rather stable orbits, at least over the studied time spans. The motion of comets outside the orbit of Saturn has been studied, in connection with the object 2060 Chiron, by Scholl (1979) and O toka and Everhart (1979); these researches have confirmed that objects in such a dynamical state can evolve towards Jupiter - and become members of the Jupiter family.

The numerical simulations would also predict the presence of a large number of comets with perihelion distances so large to inhibit the formation of the coma. Most of these objects are unobservable with the present techniques, but the finding is supported by the discovery, in recent years, of objects with perihelion close to, or even outside, the orbit of Jupiter: these could be the brightest members of that population.

Strong gravitational interactions with the major planets, occurring during close encounters, have been investigated by several authors, either using a Monte Carlo approach (Rickman and Vaghi, 1976; Froeschlé and Rickman, 1980), or with a direct integration of a large number of such events (Carusi and Pozzi, 1978; Carusi et al., 1979; Carusi and Valsecchi, 1979, 1982a,b; Carusi et al., 1981; Rickman and Malmort, 1981; Carusi et al., 1983). It is remarkable that all the patterns at close encounters, and the possible orbital evolution-
ions after them, found in the case of real objects have also been found in these numerical experiments, thus confirming that the most common dynamical phenomena related to close encounters with the giant planets have been identified.

7. CONCLUSIONS

As we have seen, most aspects of the dynamical evolution of SP comets are at least qualitatively understood; a definite improvement in our knowledge of this field would come from better quantitative assessments of the probabilities of the various processes, and this will require more sophisticated and extensive computations than those performed so far.

A further step may then be the Interfacing of dynamical studies with physical ones, as the space missions and the ground based observations give us more realistic models of the characteristics and the behaviour of cometary nuclei in the vicinity of the Sun.

REFERENCES


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DISCUSSION:

Olsson-Steel: How was P/Halley captured? Encounters with Jupiter are of very low-efficiency since g < 0.6.

Carusi: Although the efficiency is very low, P/Halley has had several encounters rather close to Jupiter; most probably the closest, and best oriented, of them has brought the comet where it is now.

Mamajkiewicz: Is it possible that nongravitational effects could change the patterns of motion you have presented, especially the resonant cases?

Carusi: It is certainly possible. We have not modeled the nongravitational forces, because they are unknown for most comets. Taking them into account, the patterns, especially in cases of resonances, must be slightly different and this difference should accumulate with time.
LONG-TERM RESONANCES AND ORBITAL EVOLUTIONS OF HALLEY-TYPE COMETS

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Backward integrations of motion of the Halley-type comets, covering over 11,000 years, are used to investigate their librations around high-order resonances with Jupiter. These occur for comets moving in direct orbits with revolution periods between 50 and 90 years. The fact that about one half of the time they are librating at a time explains the occurrence of revolution periods in this range. The librations are of rather uniform period and amplitude, and tend to persist over about 200 revolutions of the comet. Their presence implies that the lifetimes of these comets since their captures into periodic orbits of small perihelion distance mostly exceed 300 revolutions. Possible exceptions among the 9 comets with present periods of 50 to 90 years are the already extinct P/Westphal, and also P/Halley, for which a close approach to the orbit of Jupiter 150 revolutions ago was identified.

1. INTRODUCTION

Currently we know 19 comets with revolution periods between 20 and 200 years (Marsden, 1986), which are conventionally referred to as comets of Halley type. Another three comets have periods of less than 20 years, but the low values of their Tisserand invariants with respect to Jupiter, $T < 2$, are indicative of their similar dynamical history (Carusi et al., 1986). In spite of the very limited statistical sample, it was recognized long ago that there is a significant overabundance of periods around 70 years, pointing to a mechanism concentrating the comets into this region, or letting them stay there for a longer time. An appropriate mechanism was suggested in our previous papers (Carusi et al., 1985 and 1987), where we have found librations of some comets around the 5:1, 6:1 and 7:1 resonances with Jupiter, stabilizing temporarily their stay in this region.

The integrations on which this conclusion was based (Carusi et al., 1985) spanned an interval of $3 \times 10^5$ days, 1585 AD to 2406 AD. This would typically include only two full libration cycles. In order to get a better insight into this phenomenon we have performed backward integrations for another $4 \times 10^5$ days, 1985 AD to 9367 BC. The whole period covered by computations was equivalent to 30 typical libration cycles, and 1000 revolutions of Jupiter, allowing to check the persistence of the resonances and the transitions between different types of motion. Also, the extended time span is about the same as the probable active lifetimes of Halley-type comets, so that it might encompass some captures of these comets from long-period orbits.

2. THE METHOD OF COMPUTATION

The longer time span to be covered by numerical integrations required some major changes against the method used in the Long-term Integration Project (Carusi et al., 1985). The use of planetary coordinates from the JPL Long Ephemerides DE-102 could not be maintained, because this only covers less than one half of the time span required. It was therefore decided to integrate the whole system of planets and comets in heliocentric coordinates using Cowell's method and, as before, the RADAU integrator by Everhart (1985).

Since our computer had a 64-bit word length (in double precision), the 15-th order version of RADAU was used, putting the control parameter LL, on which the accuracy of the integration depends, equal to 8. For more details see Everhart (1985).

In order to keep the integration time reasonably short, it was decided to limit the number of perturbing planets to seven, disregarding Mercury and Pluto; the mass of the former was added to that of the Sun. The nongravitational effects, which are only known for five Halley-type comets of more than two apparitions (Marion, 1985) and cannot be extrapolated with confidence, were disregarded. All the Halley-type comets included in the LTEP were integrated backwards from JD 2300000.5, which was the end point of our previous computations. The starting positions and velocities of the comets were those obtained for this date in the LTEP. The starting positions and velocities of the planets were taken again from DE-102, with appropriate corrections taking into account that the Sun and Mercury were replaced by a single body in their barycenter. The integrations spanned over $4 \times 10^5$ days (nearly 11,000 years), from 1585 AD to 9367 BC, and the CPU time on the FPS 364 was less than 8 hours.

3. THE MAIN RESULTS

In this paper we concentrate on the results on the nine comets with revolution periods between 50 and 90 years, in that range where the librations were found (Carusi et al., 1986): around the 6:1 resonance for P/Bronselen-Metcalf, P/Olbers, and P/Pone-Brooks, that of 5:1 for P/Dubiago, and that of 7:1 for P/Vaisala 2. The evolutions of the orbital periods of these comets according to the extended integrations are shown in Fig. 1. The periods are referred to that of Jupiter, and computed at each aphelion passage from the semimajor axis of the osculating barycentric orbit. The values obtained in this way are much closer to the actual duration of the revolution than the generally used values of the osculating period at perihelion, since for most of the time the actual rate of motion of a comet of Halley type is best approximated by this barycentric orbit.

For the period of $\pm 400$ years from now (Carusi et al., 1987), P/Bronselen-Metcalf and P/Pone-Brooks were found to librate around the 6:1 resonance all the time, while P/Olbers was escaping from it at the end. In the extended backward computations, P/Bronselen-Metcalf remains in this libration until the end of integration, but the behaviour of P/Olbers and P/Pone-Brooks is reversed. The former librates all the time, whereas the libration of the latter can be only traced back to $\sim 1600$ BC. The onset of libration at that time is followed by a progressive diminution of the period of the libration cycle, and damping of its amplitude.
Figure 1. The changes in the revolution periods of five Halley-type comets subject to temporary librations around high-order resonances with Jupiter. Horizontal scale, time in millennia BC; vertical scale, barycentric revolution period at aphelion, in units of the revolution period of Jupiter.

Another conspicuous example of long-term libration is P/Dubiago. Some differences against P/Brorsen-Metcalf and P/Olbers only appear when the horseshoe patterns reconstructed from the relative positions of Jupiter and the comet, at its individual perihelion passages, are intercompared. While the occupied arc in such a diagram exceeds considerably 180° for P/Dubiago, it is smaller than this for the other two long-librating comets. Towards the end of the backward integration, nearly 10,000 years ago, the libration of P/Dubiago vanishes in two successive steps, indicative of its capture into resonance. P/Vaisälä 2 shows, in addition to the two cycles already recognized in the LTEP (Carusi et al., 1987), only two incomplete cycles immediately preceding. For the remainder of the extended integrations it displays a chaotic behaviour, but its revolution period remains confined within rather narrow limits - only 2 to 3 times broader than the libration amplitude.

The dynamical evolutions of the remaining four comets, showing no signatures of librations, are plotted in Fig. 2. The periods of P/Halley and P/Pons-Gambart, moving in retrograde orbits, and of P/DeVico, with inclination close to 90°, oscillate with moderate amplitudes without crossing their neighbouring n:1 resonances. In some sense, this is a direct counterpart to the prograde librators. The double-periodic oscillations of the period of P/Halley during the last four millennia are quite interesting. They may explain the partial success in linking up its different apparitions by empirical formulae, as first applied by Angström (1862) and developed by Kamienski (1961). However, any extrapolation of this kind must break down completely less than 60 revolutions back, when the pattern changes abruptly, and again 5 revolutions from now, when the comet approaches the 6:1 resonance with Jupiter (Carusi et al., 1987).

Most chaotic is the motion of P/Westphal, the revolution period of which varies quite irregularly between 55 and 130 years. It must be emphasized that the past dynamical history of this comet is very poorly determined because its descending node remains for the last five millennia within 0.5 AU of the orbit of Jupiter. Thus it appears possible that the comet was captured from a long-period orbit during this time span.

No similar crossings are indicated by the backward integrations of the other eight comets, which suggests that they have already spent more than 11,000 years, or at least 130 to 200 revolutions,
in periodic orbits similar to the present ones. Of course, for the one-apparition comets - in particular - P/Pons-Gambart, this conclusion has to be taken with reserve, due to their poorly determined starting orbits.

Most interesting is the case of P/Halley. Kozai (1979) has suggested that its argument of perihelion librates very slowly between $\omega = 47^\circ$ and $133^\circ$. Our integrations cover only about 30% of Kozai's cycle, but at the end $\omega$ stops a little below $45^\circ$. At the same time, the descending node approaches the orbit of Jupiter within 0.15 AU, and remains at this distance for a number of revolutions of the comet. P/Halley exhibits the largest progressive variations of the orbital inclination, from $162^\circ$ to $145^\circ$, going back in time; for all the other comets the total change is $\pm 5^\circ$ or less. As it can be seen from Table I, its argument of perihelion is precessing most rapidly, too. For the next two comets with high precession rates, P/Brosen-Metcalf and P/Olbers, $\omega$ does not recede from 90° far enough to enable the comet to approach the orbit of Jupiter.

The total changes of the orbits of these nine comets are summarized in Table I. This lists, in succession: the names of the comets preceded by their numbers from our catalogue (Carusi et al., 1985); the number of apparitions $A$, indicative of the degree of accuracy of the starting orbit; some important orbital elements - perihelion distance $q$, inclination $i$, argument of perihelion $\omega$, and revolution period $P$ - the first figure referring to the starting (present) orbit and the second to that at the end of the extended backward integrations, 9367 BC; the resonance ratio $R$ around which the comet librates, or was librating in the past, or the resonance values of $n$ in $n:1$ between which it remained confined for the whole integration period (in parentheses); the degree of accuracy of the starting orbit, between the beginning and the end of libration, $B$ and $E$; the average duration of one libration cycle $D$ (in years); and the number of the libration cycles $N$ identified in our computations.

Among the other comets of Halley type, not included in Table I, there are several interesting cases of temporary librations persisting over 4 to 8 cycles. What they have in common is just a concentration of the libration periods around $\pm 500$ years. Otherwise, there is a broad variety of the resonance ratios (7:4 for P/Hartley-IRAS, 5:2 for P/Crommelin, 3:1 for P/Stephan-Oterma, 9:1 for P/Brофfield, 11:1 for P/Swift-Tuttle), and resonance patterns. The general impact of these resonances on the dynamical evolution of the system of comets is evidently of secondary importance, and they will be discussed in a separate paper.

### Table I

<table>
<thead>
<tr>
<th>Comet</th>
<th>A</th>
<th>q</th>
<th>i</th>
<th>$\omega$</th>
<th>$R$</th>
<th>P</th>
<th>B</th>
<th>E</th>
<th>D</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 P/Brosen-Metcalf</td>
<td>2</td>
<td>0.48/0.53</td>
<td>19/14</td>
<td>129/70</td>
<td>72/72</td>
<td>6:1</td>
<td>&lt; -9400</td>
<td>&gt; 2400</td>
<td>360</td>
<td>33</td>
</tr>
<tr>
<td>15 P/Olbers</td>
<td>3</td>
<td>1.18/1.27</td>
<td>45/45</td>
<td>65/108</td>
<td>70/73</td>
<td>6:1</td>
<td>&lt; -9400</td>
<td>&gt; 2300</td>
<td>360</td>
<td>30</td>
</tr>
<tr>
<td>14 P/Pons-Brooks</td>
<td>1</td>
<td>0.77/0.87</td>
<td>74/71</td>
<td>198/211</td>
<td>71/76</td>
<td>5:1</td>
<td>1000</td>
<td>&gt; 2400</td>
<td>340</td>
<td>9</td>
</tr>
<tr>
<td>519 P/Dubiago</td>
<td>1</td>
<td>1.11/1.06</td>
<td>22/20</td>
<td>97/92</td>
<td>62/64</td>
<td>5:1</td>
<td>-7700</td>
<td>&gt; 2400</td>
<td>340</td>
<td>30</td>
</tr>
<tr>
<td>521 P/Väisälä 2</td>
<td>1</td>
<td>1.29/1.41</td>
<td>38/37</td>
<td>335/328</td>
<td>85/87</td>
<td>7:1</td>
<td>1000</td>
<td>&gt; 2400</td>
<td>360</td>
<td>4</td>
</tr>
<tr>
<td>1 P/Halley</td>
<td>30</td>
<td>0.59/0.88</td>
<td>162/145</td>
<td>112/45</td>
<td>76/78</td>
<td>6:1</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>506 P/DeVico</td>
<td>1</td>
<td>0.66/0.72</td>
<td>85/82</td>
<td>13/10</td>
<td>76/77</td>
<td>6:1</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>505 P/Pons-Gambart</td>
<td>1</td>
<td>0.81/0.91</td>
<td>136/139</td>
<td>19/398</td>
<td>57/58</td>
<td>4:5</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 P/Westphal</td>
<td>2</td>
<td>1.25/1.77</td>
<td>41/46</td>
<td>97/76</td>
<td>62/68</td>
<td>-</td>
<td>-</td>
<td></td>
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</tbody>
</table>

4. DISCUSSION AND CONCLUSIONS

The long enduring librations of the Halley-type comets around high-order resonances with Jupiter, as demonstrated by integrations of their motions over 12 millennia, explain their overabundance in the range of revolution periods between 50 and 90 years. From among the nine comets occupying this range at present, two - P/Halley and P/Pons-Gambart - move in retrograde orbits. Hence, for the reasons explained in more detail elsewhere (Carusi et al., 1987), they are not liable to this type of libration. The repetition of similar patterns between two neighbouring resonances $n:1$ is rather the result of the opposite effect, repelling the comet periodically from its resonance. This would restrict the number of candidates for librations to seven.

The starting orbits of these comets are of different accuracy, by which they can be divided into two groups. P/Pons-Brooks, P/Olbers, P/Brosen-Metcalf and P/Olbers have been observed at 3 or 2 apparitions, respectively, so that their present revolution periods are well determined. The nongravitational effects are only known for the former two comets (Marzari, 1985). Since their sum over one libration cycle amounts to less than 1/10 of the mean amplitude, it appears improbable that they would be able to destroy the libration pattern. The main source of uncertainty is that of the present osculating periods of the three comets of only one recorded apparition: P/Dubiago, P/Väisälä 2, and P/DeVico. This makes about 2 years, and equals to the mean amplitude reached by the librating comets during one cycle. Accordingly, the librations of P/Dubiago should only be real if the actual error is positive or small. Circumstantial evidence, provided by the distribution of the well determined periods of other comets with respect to the resonances, implies a probability of well over 50%. The capture of P/Väisälä 2 into libration, found to have occurred 15 revolutions ago, is questionable. It might have taken place much earlier, or not at all. The orbit of P/DeVico is of very high inclination, varying between $82^\circ$ and $85^\circ$. Therefore, it appears highly questionable whether the libration mechanism could work in this case with any starting period. The evolutions of P/Pons-Brooks and P/Väisälä 2 suggest that a comet has to spend some time in the vicinity of a resonance, until a suitable configuration triggers the libration. This would be the result of the opposite effect, repelling the comet periodically from the resonance. The repetition of similar patterns between two neighbouring resonances $n:1$ is rather the result of the opposite effect, repelling the comet periodically from its resonance. This would restrict the number of candidates for librations to seven.

Even for the best determined orbits it is possible to rely on the positions of the comet on its orbit and ellipse, and to identify its encounters with the planets, only for a small fraction of the period covered by our backward integrations (see, e.g., Sitarski and Ziołkowski, 1986 for P/Halley). However, if there are librations preventing planetary encounters, both of these restrictions lose their meaning. Even for the one-apparition comets - in particular - P/Pons-Gambart - move in retrograde orbits. Hence, for the reasons explained in more detail elsewhere (Carusi et al., 1987), they are not liable to this type of libration. The repetition of similar patterns between two neighbouring resonances $n:1$ is rather the result of the opposite effect, repelling the comet periodically from its resonance. This would restrict the number of candidates for librations to seven.
comets moving in direct orbits, the share is over 50\%, and for \( i < 60^\circ \), 70 \%. A typical duration of the librating motion is about 15,000 years, or 200 revolutions of the comet. An average libration cycle covers 350 to 400 years, or a little over 30 revolutions of Jupiter. This is 2.0 to 2.5 times longer than a typical cycle of a comet of the Jupiter family, librating temporarily around the 1:2 resonance, or of a steadily librating Trojan. On the other hand, one cycle covers only five to six revolutions of the comet. It is also interesting that, when all the Halley-type comets are taken together, the 20 \% proportion of temporary librators is just the same as in the Jupiter family of comets, and substantially higher than the proportion of permanent librators among the asteroids.

The durations of the librations of Halley-type comets indicate that their active lifetimes after their captures from long-period orbits of large perihelion distance are mostly longer than 20,000 years, or 300 revolutions. Curiously enough, the only comet with revolution period between 50 and 90 years which might be much younger, P/Westphal, is the only one which has already disappeared.

An object of special interest is P/Halley, for which more reliable data on the past activity and present mass loss exist than for any other comet. At the end of our backward integrations, its perihelion distance is 1.5 times larger than today, suggesting a slower disintegration rate. At that time, the descending node remains fixed near the orbit of Jupiter for a number of revolutions, permitting strong perturbations. This configuration substantiates the conclusion that the comet could have been captured from a long-period orbit about 150 revolutions ago. Due to a high relative velocity, the encounter would have had to be a very close one. To explore this possibility in more detail, we plan modelling experiments with sets of objects revolving in orbits similar to that of P/Halley in the critical period.

ACKNOWLEDGMENT. Our computations were made possible by a grant from the Piano Spaziale Nazionale CNR, which is gratefully acknowledged.

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The planetary origin of fireballs

The original hypothesis of the primordial origin of comets assumed the existence of two types of materials in interplanetary matter: primordial and planetary. The primordial material should be the remnants of an interstellar nebula, now mostly contained in comets (Whipple, 1952). The planetary material represents all known types of meteorites (Jakes, 1978).

According to Ceplecha and McCrosky (1976), there are two groups of planetary material (I, II) and two groups of primordial material (III A, III B) among the fireballs, particles with masses in excess of 0.1 kg. However, the testing of all four groups of fireballs with the aid of the theory of atmospheric terminal heights has disclosed that only planetary material probably exists among fireballs (Padevíc, 1987).

The theory of terminal heights predicts two basic types of fireballs: a) fireballs with a subcritical entry mass may reach the Earth as compact meteorites, b) fireballs with an overcritical entry mass disintegrate into dust already at high altitudes as a result of the aerodynamic pressure being higher than the ultimate strength of the material in question. All fireballs of Groups I and II are subcritical. There is no doubt about the planetary origin of the fireballs of Group I, because three falls of meteorites have already been recorded in this group (Pfibram, Lost City, Innisfree). The fireballs of Group II cannot be carbonaceous CI-meteorites, as assumed by Ceplecha and McCrosky (1976), because they terminate as much as 30 km lower than would correspond to their characteristic ultimate strength of 0.1 MPa. The author assumes that this group involves namely L-chondrites of typically planetary origin. The most brittle CI-meteorites of planetary origin (Jakes, 1978), can only be found among the fireballs of Group III B. A part of these fireballs with subcritical masses may reach the Earth's surface as meteorites, the other part of overcritical fireballs will not penetrate deeper than the altitude of 55 km, which corresponds to the characteristic aerodynamic pressure of 0.1 MPa. The slightly stronger C2-meteorites of planetary origin might belong to fireballs of group III A which are able to penetrate to depths corresponding to aerodynamic pressures of 0.6 MPa.

2. Planetary origin of comets

Since the fireballs of Groups III A and III B are formed of carbonaceous, surface, planetary material with typical cometary orbits in the Solar System, then comets are probably of planetary origin. The possible explosion of a large planet is discussed again. This time on the basis of gravitationally decelerated expansion of an originally superdense embryo.

All known groups of fireballs contain bodies which may reach the Earth's surface as meteorites and are of planetary origin. Since some fireballs have cometary orbits in the Solar System, then comets are probably of planetary origin. The possible explosion of a large planet is discussed again. This time on the basis of gravitationally decelerated expansion of an originally superdense embryo.

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2. Planetary origin of comets

Since the fireballs of Groups III A and III B are formed of carbonaceous, surface, planetary material with typical cometary orbits in the Solar System (Ceplecha and McCrosky, 1976), we can present a second hypothesis, i.e. that comets are probably of planetary origin. The comets would have to be segregated from the early planets by an unknown process, as indicated by the age of the meteorites: 4.6 x 10^9 years.

Anders (1975) claims the origin of carbonaceous meteorites to be on the surface of the planet close to the Sun, probably between Mars and Jupiter. Van Flandérn (1978) considered the explosion of parental comet planet with a mass equal to 90 Earth masses in the same region. According to Weissman (1985), the sum of the masses of all comets in the inner and outer Oort's cloud is even higher, comparable with the mass of Jupiter. However, according to Wood (1967), meteorites originated from a larger number of smaller parental bodies. Nevertheless, this could have involved only significant inhomogeneities in the early mantle of a single large body (Nagy, 1975) with a cometary carbonaceous and volatile surface layer.

Various types of meteorites indicate an onion-like structure already of the early parental planet with an iron core and silicate mantle. If this structure is due to heterogeneous accretion (Rudnik and Sobotovich, 1984), the cause of the explosion of the parental planet of the comets cannot be found (Weissman, 1984). The explosive model is founded on an analogy between the interior of the planet and the onion-like structure of a Type II supernova. The gravitational collapse of a massive star would generate a series of nuclear fusions, beginning with the formation of helium from hydrogen and ending with the generation of iron from silicon (Bethe and Brown, 1985). An analogous series of explosive fusions, but in opposite order of onion-skin generation, may take place in the expansion of a miniature superdense embryo of a planet. If the original embryo were of hydrogen and had not expanded too much, all the fusions as far as iron could have taken place in it, as can be seen in iron meteorites. Under rapid adiabatic expansion, the pressure and temperature of hydrogen in a larger volume decrease, so that the fusion in the next layer ends with silicon as can be seen in stone ordinary chondrites. In the yet higher and cooler layer the fusion ends with oxygen and later carbon, evidence of which can be found in completely oxidized carbonaceous meteorites. The expansion of the planetary embryo ends by the creation of a hydrogen-helium atmosphere, partly preserved in comets.

All the inner planets may have originally
been more massive than today's outer planets. Their outer layers of lighter elements may have been segregated during their explosive evolution. According to McCreas (1972) inner planets can be formed from giant planets of the Jupiter type if they lose 99% of the light elements. Therefore, the masses of all early planetary embryos could have grown monotonically with decreasing distance from the Sun, which was the most massive of all planets.

3. The explosive origin of the Solar System

We can formulate a third hypothesis of the explosive origin of the Solar System as a whole from an interference embryo roughly 26 orders of magnitude smaller than the present radius of Neptune's orbit. The origin of embryos of all cosmic objects can be sought in the early dense Universe and not later when the temperature has already dropped to such an extent that gravitational collapse of the expanded mass could have occurred. Pre-galactic and pre-stellar disturbances in the structure of the Universe which, according to Gurevich and Chernin (1987), must have been much more severe than the level of thermal fluctuations throughout the Universe's history, cannot be explained otherwise.

If the threshold temperature of 10^{13}K was exceeded in the Hadron era of the Universe, thermal collisions exceeding 1 GeV in energy occurred. These high-energy collisions resulted in the generation of clusters of new protons and their anti-particles (Albrow, 1979). These clusters of hydrogen nuclei formed the base of a new type of strong, internally ordered inhomogenities comparable in size with the wavelength of the Doppler's mass waves of particle occurrence probability,

\[ \lambda = \frac{\hbar}{m c} (1 - \frac{\beta^2}{c^2})^{\frac{1}{2}}, \]

where \( \hbar \) is Planck's constant, \( c \) the speed of light, \( m \) the mass of the particle at rest and \( \beta \) its relative velocity.

The disturbances in the distribution of particles generated by the interference of mass waves expanded much more slowly due to their own gravitation than the surrounding Universe, and could have been the foundation of superdense embryos of galaxies, stars or planets.

The headon collision of electron-positron beams at high energies has the simplest result (see Fig. 1a). The coordinates of the interference maxima are given by the relations

\[ x = \sqrt{2} \frac{\lambda}{(n^2 + 4an^2 + a^2 n^4 + 1)^{\frac{1}{2}}} \]

\[ y = \frac{\beta}{c} (n^2 + 2an) \]

under the condition that

\[ a = d/\lambda \quad n = 0, 1, 2, 3, \ldots \]

where \( n \) is the interference order and \( a > 0 \) is a continuously varying parameter. Collisions of local importance take place in the maxima of the interference phenomenon.

This theory describes the geometry of the interference phenomenon caused by two wave point sources at distance \( d \) apart. The history of the collision of headon particle beams can be divided into three phases (see Fig. 1a). Just before the collision, when \( d > \lambda \), a complicated interference phenomenon is generated by the approaching leptons, which has a nearly spherical envelope (see Fig. 1b). During the actual collision, when \( d = \lambda \), the lepton interference object gains in intensity and reduces to a disk formation of zero order and two rod-like formations of the first order positioned perpendicularly and symmetrically relative to the disk. After the collision, when \( d < \lambda \), two hadron jets begin to emanate under angle \( \phi \) in the direction of quarks and anti-quarks (Albrow, 1979).

![Fig. 1](attachment:image.png)

**Fig. 1** The headon collision of electron-positron beams at high energies

Their mass waves interfere and first form a single hadron object of zero order in the form of a disk (see Fig. 1b). Its existence follows from Eqs (1) to (4) for \( d = \lambda \). If coordinates \( x \) and \( y \) in them are replaced by new coordinates \( x' \) and \( y' \), As the jets of new hadrons recede from each other, all typical interference objects, including the spherical, which however grow weaker, can be formed in the opposite order.

The superdense embryo of the cosmic object is generated if the number of newly created pairs of hadrons greatly exceeds the mass of the planet, star or galaxy. When the internal pressure and temperature decrease after the particle pairs have been annihilated in the embryo and after it has expanded, the gravitational forces may terminate its further growth. If the gravitation is insufficient, the object loses its identity and is dispersed in interstellar or interplanetary matter.

According to the interference theory, the disk-like embryo has its internal structure, provided the interacting particle beams \( A \) and \( B \) have non-zero radii \( d \) (see Fig. 2). The disk is then divided into discrete interference rings with the radii

\[ r_k = \frac{\lambda}{k} \left\{ k^2 + 2k \left[ \frac{(2k)^2 - 1}{4} \right]^{\frac{1}{2}} - 1 \right\}, \]
where
\[ J = \left[ 8F^2k^2 - k^4 - 4F^2(L^2 + AF^2) \right] \left[ 16F^2 - 4k^2 \right]^{-1}. \]

Radii \( r_k \) form a harmonic series, whose number of terms is limited by the condition
\[ 2F - 1 \geq k = 0, 1, 2, 3, \ldots \]

where \( F = d / \lambda \) and \( k \) is the interference order.

Fig.2 The disk-like embryo and its internal structure

If the interacting beams display a discrete structure, instead of concentric pipes we obtain a system of interference spots which are already very close to the idea of super-dense planet embryos. If the expansion rate of the embryo of the whole Solar System does not depend on \( r_k \), no agreement with the Titius-Bode rule can be achieved.

<table>
<thead>
<tr>
<th>REFERENCES</th>
</tr>
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<tbody>
<tr>
<td>Weissman, P.R.: 1985, The Oort Cloud in Transition, Cometary Science Team Preprint Series, No. 73, Jet Propulsion Laboratory, Pasadena, California.</td>
</tr>
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</table>

DISCUSSION

Kresáč: The geocentric velocities of long-period comets are so high that their disintegration products cannot survive the atmospheric passage as meteorites. So I do not see how the laboratory analyses of meteorites might support your point of view. The hypothesis of a planetary origin of comets is very old, but it was found untenable when reconciled with their observed properties, such as the location, mass and dynamical evolution of the Oort cloud. There are additional arguments against the origin of comets too close to the Sun. Any revival of the planetary hypothesis would require first to explain these fundamental contradictions.
Mechanisms currently under consideration for the evolution of cometary nuclei are reviewed. Attention is paid to processes that should have occurred in the past history of observed comets, related to their origin or storage in the Oort cloud, but emphasis is placed on presently observed evolutionary effects and in particular the late stages characteristic of short-period comets. Evidence from brightnesses and non-gravitational forces is discussed and support for a scenario of dust coverage coupled to the evolution of perihelion distance is found. However, for the cases of comets P/Halley and P/Encke where the perihelion distance is unusually small an ultimate fate of complete mass loss or disintegration cannot be excluded.

1. INTRODUCTION

Comets are of long-standing interest in cosmogonical theory. To reveal their physical nature appears a difficult, yet highly rewarding goal of research, and the same holds for the attempts to clarify their spatial distribution and dynamical characteristics. As progress has been made in these respects, the cosmogonical interest in cometary nuclei has tended to focus on their "primordiality": their potential of offering pristine samples of pre-planetary matter from the outer parts of the solar nebula.

How, then, do these bodies evolve? This is a fundamental and often posed question, obviously stimulated by the fact that comets are one of the few classes of celestial bodies where one actually sees evolution going on. But the standard problems of what characterizes the present evolution, and what are the end states thus approached, is now supplemented by the equally important issue of what evolution has already taken place (see Weissman, 1986a). How pristine are the cometary nuclei and what are the processes by which they may have changed since their time of formation 4 billion years ago?

2. EARLY STAGES OF EVOLUTION

2.1 Evolution Driven by Internal Heat Sources

To discuss the present state of knowledge, or uncertainty, as regards these processes which should have occurred very long ago, it is advantageous to start from expected scenarios based on laboratory experiments or physical intuition. In what ways should a cometary nucleus evolve according to our understanding of a dusty snowball orbiting in interplanetary space? And how could observations of present-day comets be expected to distinguish between different alternatives?

One class of hypotheses deals with thermal evolution. The cometary nuclei appear to have formed at very low temperatures (Tanamoto, 1985; Tanamoto and Kosaka, 1987) and thus their material may have included some reactive or energetic components which may give off latent energy by means of exothermic chemical reactions or phase transitions. Some examples are free radicals formed by UV radiation in the volatile mantles of pre-cometary grains, as incorporated into Greenberg's picture of comet origin (Greenberg, 1982, 1986a); and the ion molecular clusters proposed by Shulman (1983). An important problem is to what extent these energy carriers would have been "killed" already before the formation of the comet nucleus, either by heating events in interstellar space or the presolar nebula leading to organic residues like the "yellow stuff" (Greenberg, 1982, 1986a), or by the action of mobile quenching agents such as hydrogen atoms (Wallis, 1986). Those which survive until the birth of the nucleus are likely to give off their energy later on, as the local temperature reaches a critical value.

The thermal evolution of the cometary nucleus thus may be influenced by an internal heat source which becomes active at a certain critical temperature. There may be several such sources with different temperatures and different energy yields. Assuming the dominant mode of energy transport to be the bulk conductivity of the solid material, the time scale of heat diffusion over the radius of the nucleus can be estimated at \(-10^7\) yrs using the thermal diffusivity of compact ice (Klinger, 1981, 1985). If the structure of the nucleus is quite porous (Rickman, 1986; Whipple, 1986), this may be somewhat longer, but it is certainly much shorter than the typical residence time expected for Oort cloud comets. Thus even if a substantial heating should have occurred initially, the nuclei would have had time enough to cool down before entering the inner solar system. On the other hand, thermal diffusion is slow enough that one may imagine a central part of the nucleus where heat release has occurred practically instantaneously, surrounded by a thermal discontinuity expanding into colder, unaltered material (Fig.1).

Such an outward propagation will necessarily stop if the nucleus has a strong underlying temperature gradient so that the discontinuity reaches material that is too cold to be heated to the critical temperature, but such gradients would be expected only under special conditions, if attention is restricted to cometary formation in the outer parts of the solar nebula.

In addition to the above-mentioned chemical transformations, there is a number of possibilities concerning low-temperature phase changes of water ice (see Whalley, 1985). It appears difficult to specify in detail the sequence of events that may have taken place by consecutive reactions and phase changes upon an initial slight heating, e.g. by radioactive decay of isotopes with short half-lives. But one may expect the basic structure of the ice to remain amorphous (Smoluchowski, 1985) since the crystallization temperatures to cubic and hexagonal ices are as high
as -150 K (Klinger, 1981; Prialnik and Bar-Nun, 1987). This crystallization is rather expected to occur in the later stages of evolution as the comet is captured into the inner solar system and the nucleus is strongly heated from the outside by absorbed sunlight.

Radioactive decay is an interesting possibility as a stimulus for thermal evolution. Isotopes with half-lives much longer than the heat diffusion time scale can not have any major effect, but ³⁷Al might be a possibility, decaying in a mere 7*10⁵ yrs. Are again facing a difficulty in estimating how much of this heat source may have been incorporated into the comet nuclei: ³⁷Al should have originated in a supernova event closely preceding the birth of the solar system (Lee et al., 1977), but there is an obvious need to have comet nuclei formed within ~10⁶ years of this event for the heat source to be significant.

In an extreme case, this heat might have sufficed to melt the ice in a large fraction of the nucleus (Wallis, 1980; Irvine et al., 1980), but in such a case one would expect both a fairly high density and a chemically differentiated structure (Fig. 2), perhaps with a silicate core surrounded by an icy mantle, all wrapped up in an outer layer of more or less pristine material. One characteristic of cometary nuclei that now appears more clearly than before, using recent observations of P/Halley and other comets, is that they do not have this structure. In particular, their densities appear far too low (Rickman, 1986, 1987; Rickman et al., 1987). Thus there is some observational evidence against the existence of early thermal events strong enough to have caused major structural changes of the nuclei. But this evidence does not put constraints on moderate thermal events corresponding to phase changes or release of primordial chemical energy. In principle, polymerization of carbon compounds could have offered a major energy source (Wallis, 1986), but the formaldehyde polymers tentatively identified in comet Halley (Huebner et al., 1987) may have been formed in a pre-cometary stage (op.cit.).

2.2 Evolution Driven by Surface Heating

According to a nowadays commonly accepted picture of comet formation having occurred relatively far from the Sun (~10-1000 AU; see Weissman, 1986a; Tamamoto and Kozasa, 1987), the above described effects should have been practically independent of insolation-induced heating. But as the comet finally approaches the Sun, one may expect additional evolutionary effects from the heating of the surface layer by sunlight. Of course a thermal wave will penetrate toward the interior of the nucleus, and along with this wave goes, probably, crystallization of the ice. One may easily speculate about observable consequences of this exothermal phase transition, which may increase the local temperature by 20-30 K (Smoluchowski, 1981) and thus significantly modify the sublimation rate if it occurs near the surface. In particular, there have been suggestions as to the high activity of newcomers from the Oort cloud at large heliocentric distances (Smoluchowski, 1981); erratic activity like the outbursts of comet P/Schwassmann-Wachmann 1 in this distance range (Patalnik et al., 1974; Froeschlé et al., 1983); and the activity pattern of comet P/Halley including its perihelion asymmetry of gas production (Rickman et al., 1985). But modelling is of course needed, and this turns out to be a non-trivial task. A very crude treatment was first done by Herman and Podolak (1985), and recently important progress was also achieved by Prialnik and Bar-Nun (1987). The latter authors concentrated on the orbit of comet Halley, and from their work it appears that the phase change quickly penetrates to a depth of nearly 100 m and then comes to rest until sublimation carries the surface close enough, whereupon a new penetration event carries crystallization even further down. After several such events occurring within several hundreds of orbital revolutions the nucleus appears to crystallize completely, and the interior then finally relaxes to the orbital mean temperature (Klinger, 1983) of approx. 80 K. Typical evolutions thus expected upon captures into Jupiter family orbits are still to be explored.

Other consequences of the thermal wave might include thermal cracking due to the strong and rapidly changing near-surface temperature gradients (Kührt, 1984; Kührt and Möhlmann, 1984; Kührt et al., 1986), or indeed the density change that may accompany the phase transition, but this idea should be reconsidered in the light of recent data. In particular, can a very porous snow-drift-like mixture of grains be expected to crack, or should one rather foresee some other kind of structural modification in response to the rapidly changing temperatures? In any case, spacecraft imaging of the comet Halley nucleus does seem to suggest a process related to cracking (Möhlmann et al., 1986), leading to a linear network-type arrangement of the outgassing zones. Support for this kind of pattern is also found from

Fig. 1. A cometary nucleus with a central region (r < r_c) altered by an exothermocal process with critical temperature T_c. The curve below indicates a schematic temperature structure T(r) to be expected.

Fig. 2. A cometary nucleus where melting occurred at an early stage in a large fraction of the volume. As a result, gravitational separation occurred so that the silicate dust settled at the center as an inner core surrounded by a dust-free liquid that later formed a compact ice mantle upon cooling.
the mapping of dust-emission sources (Sekanina and Larson, 1986a).

The origin of such structures may be a very important point to clarify, and this leads to one of the central issues of the problem of comet evolution: the question of chemical differentiation of the surface layers. Since cometary material is a mixture (although, perhaps a very intimate one) of components of different volatility, and there is reason to believe that the nuclei were formed homogeneous with constant mixing ratios throughout, evolution would result if upon approach to the Sun and heating of the surface layer the more volatile components escape preferentially so that they become depleted (Fig. 3). The largest dust grains, e.g., may be too heavy in relation to the gas flow from the nucleus surface and thus may form a residue remaining on the surface (Whipple, 1951; Shulman, 1972; Ip and Mendis, 1974), thereby interfering with gas production in various ways. But a differentiation of the volatile constituents with respect to depth might also occur to the extent that sublimation can proceed beneath the surface with escape of the gas through pores or cracks. The recent arguments in favour of low densities of comet nuclei (Vallis and MacPherson, 1981; Greenberg, 1986b; Rickman et al., 1987) tend to favour the idea of sub-surface sublimation even in the absence of cracks. Clearly the most attractive idea is that of volatile pockets (Cowan and A'Hearn, 1982; SöL et al., 1986) where an excessive gas pressure is gradually built up close to the surface, to cause an outburst of gas production as this gas makes its way to the surface.

Fig. 3. The surface layer of a cometary nucleus with sublimation-driven differentiation. Heat and material transfer processes are indicated to the left (after Houplis et al., 1985), and a possible grain structure is indicated to the right.

Generally speaking, as comets grow older, their volatile constituents may be buried under a less volatile material, certainly dominated by H_2O ice, which may grow thicker and thicker (Houplis et al., 1985). This, of course, may be viewed in conjunction with the general conclusion that short-period comets are in general dominated by CO (Marzari et al., 1973; Delvaem, 1985) while there is a possibility that other volatiles control the remote activity often seen in long-period comets, especially the new ones coming from the Oort cloud (Marzari et al., 1978; see also Sekanina, 1973). Recently, e.g., the record heliocentric distance of comet Stearns 1927 IV was finally broken by the observations of comet Bowell 1982 I at a heliocentric distance of 13.6 AU (Meech and Jewitt, 1987). This is related to the idea of a C02-dominated nucleus (Meech and Jewitt, 1987). There is hence some evidence that the new comet Bowell is actually CO_2-dominated. A problem is posed by the very low expansion rate of ~1 m/s of the coma (Sekanina, 1982a; Jewitt, 1984), since from the gas flux of a CO_2-sublimating nucleus grain speed ~20 m/s should be expected. One possible explanation of this discrepancy may be that the nucleus is not totally active but, perhaps, outgassing only in spots covering ~10% of the surface area so that the gas flow is strongly diluted.

2.3 Cosmic Ray Effects

If such a small free-sublimating fractional area could be demonstrated beyond doubt for a new comet, it would have interesting implications for our picture of past comet evolution. The effects of cosmic ray irradiation on cometary nuclei in the Oort cloud are of course of relevance in this context. Such effects have been recently explored by means of laboratory experiments (see Johnson et al., 1986), and it appears that during 4.6 billion years in the Oort cloud the outermost 10^3 g/cm^2 receive an integrated dose high enough to transform the material profoundly (e.g., Cooper, 1983; Ryan and Draganic, 1986). New volatile species are formed but also organic refractories, and at a density of ~0.2 g/cm^2 as indicated by the analyses of nongravitational effects (Rickman, 1987; Rickman et al., 1987) one may expect a crust of ~5 m thickness consisting of these irradiation products to cover the surface of the nuclei (see Johnson et al., 1986).

An important question, still to be answered, is what may be expected to happen to such a crust upon the first approach to the Sun. We are faced with the interesting though somewhat speculative ideas that the volatiles may sublimate away during the first perihelion passage (Whipple, 1977; Johnson et al., 1986) thus accounting for the well-known fading phenomenon first discussed by Oort and Schmidt (1951), and that the refractories stay behind thus forming a thick crust of dark, refractory material covering most of the surface of a typical short-period comet (Sekanina, 1986a; Johnson et al., 1986). It does not appear evident that this scenario actually applies, but further investigation, e.g., by theoretical modelling of the response of the irradiation-altered crust to solar heating, will at least provide some hints.

3. FINAL STAGES OF EVOLUTION

3.1 Grand Scenarios

From the most basic properties of comets we can immediately conclude that they do not last forever, at least not in the shape in which we observe them. For the final stages of evolution there are basically two grand scenarios, which may be termed the "mass loss model" and the "dust coverage model", respectively.

3.1.1 Mass Loss Model: Application to Comet Halley.

By gradual sublimation of surface layers, assuming no refractories are left behind, the nucleus shrinks as the comet passes successive perihelia (Fig. 4). As
this shrinking proceeds, the ratio of area to mass increases and thus the relative mass loss increases. There are, however, some obvious modifications to this idealized picture.

For instance, it is well known that comets are apt to splitting (Sekanina, 1982b), and even though in most cases as yet observed splitting did not imply the sudden death of the comet, the increase of sublimation area must obviously accelerate the mass loss. We may probably view cometary splitting as a part of a general disintegration process (cf. Weissman, 1986b), which ultimately amounts to the mass approaching zero, or the size passing a limiting value where the gas and dust production rates get too small to cause observable cometary activity.

Perhaps more importantly, the shrinking process should not be seen simply as that of a sphere whose radius decreases gradually. We have learnt that the nucleus of Halley’s comet is far from being spherical (e.g. Wilhelm et al., 1986) but also that it is far from being isotropic (Keller et al., 1986; Saggese et al., 1986). Gas and dust production is localized to a few major active spots, and the rest of the nucleus appears inert. It is obviously important to know the typical lifetime of an active spot. If these move around fast enough, then the evolution is that of a nearly isotropic nucleus even over a short interval of time. However, if this is not the case, as seems indicated by the good agreement between the locations of dust activity in 1910 and 1986 (Sekanina and Larson, 1986b), then one has to imagine that during quite some time mass loss is confined to some special part of the nucleus, thus digging holes at a considerable rate.

Some present “best estimates” pertaining to the properties of the nucleus of Halley’s comet are given in table 1. With a total (whole nucleus) free-sublimating area averaging ~60 km² over a whole apparition, i.e., about 16% of the available surface area, a total mass loss estimated at 3·10¹¹ kg on the basis of an average dust/gas mass ratio of 0.5 implies a loss of ~25 m of surface material in the active spots. If one could extrapolate these present conditions far into the future, one would find that the depth of each crater reaches 1 km in ~40 revolutions and then, if not before, the craters would start to set their signature on the bulk morphology of the nucleus. Considering the number of revolutions that Halley’s comet has already spent in its present kind of orbit (Yeomans and Kiang, 1981) it can not be excluded that its strongly non-spherical shape is a result of localized sublimation rather than being primordial. A major, single active spot seems to cover an area of ~20 km² (Keller et al., 1987), corresponding e.g. to a circular region of 2 km radius, so within ~10 revolutions one would have to take shadowing by the crater walls into account – however, before this these walls would probably collapse since they are eroded by sublimation (Wallis, 1986).

The remaining lifetime of P/Halley – again if one could extrapolate the present conditions far into the future – might be estimated as M/flH ~ 300 revolutions. However, one must be very cautious in applying this estimate, since it is only of zero order and neglects any future changes of the free-sublimating area. Yet another reason to doubt an estimate of lifetime based on pure mass loss is explained in the following subsections.

3.1.2 Dust Coverage Model. A different way to imagine the final stages of cometary evolution involves dust choking. The kind of dust grains remaining on the surface of the nucleus even at the orbital position of maximum gas flux will collect progressively, and thus they provide a means of covering the area of active sublimation more and more until an insulating layer of dust forms and the active area turns inert (cf. Fig. 3). As evolution proceeds, one may thus imagine a nucleus whose size changes only slightly but whose area of free sublimation decreases steadily toward zero (Fig. 5).

![Fig. 5. The dust coverage model of cometary evolution. Latitude-dependent mantle growth from patches coupled to spin axis precession is indicated.](image-url)

This simple idea follows in a straightforward manner from the basic concepts of a cometary nucleus (Whipple, 1950). Furthermore, evidence that activity of cometary nuclei is restricted to minor regions has been present since more than a century in the form of jet and fan structures of cometary comae (Sekanina, 1987), and more directly it appeared in the early 1970’s for comet P/Encke by a comparison of its photometric cross-section and free-sublimating area (Delsemme and Rud, 1973). As noted above, imaging of comet P/Halley has verified the existence of this basic structure.

Theoretical modelling was started by Shulman (1972), and the first numerical results concerning the evolution of a dust mantle were published by Mendis and Brin (1977). Their model concentrates on grains continually agitated by the gas flow so that a very loose structure is formed. Attention is not given to the secular behaviour and indeed no secular growth of the dust mantle is found when applied to the orbit of Halley’s comet. The gas flux always reaches too large values near perihelion, and the relatively thin layer already formed is blown away in the course of each perihelion passage (Brin and Mendis, 1979). The Mendis–Brin dust mantle is thus a strictly periodic, orbital one which does not explain the recent spacecraft observations of Halley’s comet, but an interesting possibility remains in letting those individual grains that are big enough stay on the surface as the mantle is blown away. One might then eventually explain the formation of a secular dust mantle that indeed choked off sublimation.

### Table 1. The Nucleus of Comet P/Halley

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Radii of best-fit ellipsoid</td>
<td>8 × 5 × 4.1 km</td>
</tr>
<tr>
<td>Volume</td>
<td>550 km³</td>
</tr>
<tr>
<td>Mass</td>
<td>1·10¹⁴ kg</td>
</tr>
<tr>
<td>Thus mean density</td>
<td>0.2 g/cm³</td>
</tr>
<tr>
<td>Active surface area on 14 Mar 1986</td>
<td>40 km²</td>
</tr>
<tr>
<td>Estimated whole-apparition average</td>
<td>30 km²</td>
</tr>
<tr>
<td>Thus including night-side spots</td>
<td>60 km²</td>
</tr>
<tr>
<td>Mass loss per apparition</td>
<td>3·10¹¹ kg</td>
</tr>
<tr>
<td>(Based on average dust/gas ratio = 0.5)</td>
<td></td>
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</table>
definitely. However, an obvious problem is to model the essentially unknown distribution of very large grain sizes (McDonnell et al., 1986; Crifo, 1987).

In the similar "fragile-sponge" model (Horányi et al., 1984) the possibility of secular mantle growth exists even for short orbital periods. The expense of assuming that the grains are very difficult to break down so that mantle erosion is essentially inhibited. If this is assumed, the dust mantle is stable and grows by sublimation from the bottom until its thickness reaches a final value large enough to choke off the sublimation completely by thermal insulation. However, even this asymptotic thickness is very much smaller than that of the radiation-altered crust discussed above.

A gas-diffusion model was described by Fanale and Salvai (1984), but diffusion actually did not occur in their numerical experiments. A more recent and more self-consistent model of this kind (Rickman and Fernández, 1986) often gave a stable dust mantle for the orbit of P/Halley with a thickness depending on the critical radius (f and Mendis, 1974) at the time of grain trapping. However, these models were computed using an extremely small mean free path of gas diffusion through the mantle, and as a result the cm-scale mantles found form a nearly complete obstacle to gas production and easily remain stable. This assumption is by no means realistic and should be checked further.

In any case all the models so far developed are unrealistic since they do not account for differences between different parts of the nucleus. Thus the whole nucleus is either free-sublimating or covered by a dust mantle. In reality the mantle should rather start out in the form of patches (Shulman, 1972; cf. Ip and Rickman, 1986), and this scenario might explain a wide variety of behaviours, including that of P/Halley with a few active spots on an otherwise inert nucleus, but still has to be worked out. Moreover, a significant question remains whether short-period comet nuclei such as that of P/Halley can really be covered and deactivated to a large extent by a "sublimation-driven" dust mantle whose thickness is typically only a few cm (Sekanina, 1986a).

3.2 Comparison with Observations

As already noted, the observable lifetimes of short-period comets are expected to be fairly short. Specifically, a number of revolutions of the order of 500 appears likely both from the number of disappearances in the short-period comet population (Kresák 1980) and from the nucleus capture rate found by Fernández (1985). Even though both sets of statistics are based on small numbers, the mutual agreement justifies a confidence in the quoted figure. In fact some support comes from dust models of long period comets (Oort, 1950; Shteins, 1972) indicating a typical number of active revolutions of the same order of magnitude.

Undoubtedly, the true reason for comet lifetimes to be limited to about 1000 revolutions may be a combination or an interplay of both the above described scenarios, and the actual mechanism may also critically depend on the orbital evolution experienced by the comet. Thus it is not certain that a distinction between the two scenarios can be made to the extent that either of them might be rejected in favour of the other. The problem is further compounded by the existence of various uncertainties and observational biases, to be briefly discussed in the following subsections.

Both scenarios naturally predict a long-term decrease of the free-sublimating area of the nucleus and thus of the absolute brightness (B), although on a shorter time scale there are some important differences to be discussed below. In the mass loss model this is due to a decrease of radius (R), but in the dust coverage model it is due to a decrease of the free-sublimating fraction (f) of the surface area. While B is not a very good discriminator of the two scenarios, the nongravitational acceleration (A) varies as f/R, so the mass loss model predicts an increase and the dust coverage model a decrease, as far as the long-term evolution is concerned. This should be understood as an "absolute" acceleration normalized to a standard heliocentric distance in the same sense as the absolute brightness.

3.2.1 Measures of age. Cometary orbits typical of the Jupiter family are subject to frequent major perturbations at encounters with Jupiter (Kresakirchak-Catumov, 1972; Carusi and Valsechi 1987). Thus, e.g., the perihelion distances (q) and therefore the aging rates change in a random manner. The dependence of aging rate on perihelion distance may not be the same for both considered scenarios, and thus given a comet with a certain orbital history different ages may have to be ascribed to the comet depending on which scenario is considered. However, such a formally correct approach appears unnecessarily complicated and in any case unfeasible.

Due mainly to the chaotic properties of cometary orbits (cf. Everhart, 1979) and the uncertain extrapolation of nongravitational effects outside the observed interval of orbital history, individual comets are basically unknown. Thus even if one takes a very simple definition of "absolute age" (Nq) as the number of orbital revolutions that the comet has spent with a perihelion distance small enough to allow significant evaporation of H2O ice (q < 2.8 AU; see Delsemme 1983), there is as yet no single short-period comet for which Nq is known.

This is of course very unfortunate, but there is a short-term substitute for Nq which appears useful to some extent. Let us define the "incremental age" (Nj) as the number of revolutions since the last significant decrease of q (q < 0.5 AU acquired in one single encounter with Jupiter). This measure of age can often be determined quite reliably from the orbital evolutions given in the catalogues by Carusi et al. (1985) and Kolyaev et al. (1986) up to Nj = 20-30, even though the dynamical models used are not of ultimate accuracy.

There is an interesting difference between the predictions of the two scenarios as far as Nq is concerned. In the mass loss model the evolutions predicted for A and B are monotonous, and perturbations of q only amount to accelerations or decelerations of the perihelion distance. A and B should be correlated with Nq but probably no more reproducibly than Nj, since the two age measures appear to be mutually poorly correlated. The situation is quite different for the dust coverage model. The stability conditions for a dust mantle are strongly dependent on the perihelion distance, and upon a significant decrease in q one may expect the relatively thin mantle formed in the earlier orbit to be blown off, later on be replaced by a new and thicker mantle. Thus the evolution predicted for f is not monotonous - at least not until the overall minimum of q is reached and nor are those predicted for A and B. Clear correlations with Nq are hence expected.

3.2.2 Evolution of brightnesses. The statistics of cometary brightnesses has been analyzed by Kresák (1974, 1985, 1986; see also Kresák and Kresáková 1987) and from these studies it appears as main conclusions: 1) that the rapid fading of short-period comets claimed by Veekshyvatvskij (1958) results mainly from instrumental effects and biases related to observing geometry; 2) that the true brightness variations of different comets are rather characterized by a large variety. Over a time span of - 10 revolutions there are some cases where a moderate fading can be discerned but even more cases where it can not. In connection with the identification of comet 1808 III with P/Grigg-Skjellerup, as an extreme though illustrative example, this comet is no longer a case of very rapid fading but instead one where hardly any
Nongravitational parameters are listed in Harsden's catalogue of cometary orbits for a large number of short-period comets. The only conclusions possible from brightness data are replacement by other comet discoveries at large \(N_j\) but for smaller \(N_j\) are likely to be discovered, and thus if the brightness of each comet decreases with \(N_j\) it will be easily discovered upon capture, when \(N_j\) is low. Hence at the smallest \(N_j\) our discoveries sample the distribution of nuclear radii down to the lowest limit. Some of these comets are lost due to more or less coincidental reasons, but the smallest ones are most susceptible to this fate. They are replaced by other comet discoveries at large \(N_j\) where the larger nuclei are sampled. Thus with increasing \(N_j\) there should be a tendency for the observed sample of comets to concentrate on larger nuclei, to the effect that the intrinsic decrease of \(A\) is practically cancelled out. We shall return to this selection effect in the next subsection.

As explained in the preceding subsection, no correlation can be observed between \(B\) and \(N_j\) since the latter is unknown. An observation of a statistical dependence of \(B\) on age would thus have to take the form of either a correlation between \(B\) and \(N_j\) or an ensemble of individual fading rates. The correlation between \(B\) and \(N_j\), which is predicted by the dust coverage model, appears impossible to observe due to an obvious bias. Comets fainter than a certain limit are unlikely to be discovered, and thus if the brightness of each comet decreases with \(N_j\) it will be more easily discovered upon capture, when \(N_j\) is low. Hence at the smallest \(N_j\) our discoveries sample the distribution of nuclear radii down to the lowest limit. Some of these comets are lost due to more or less coincidental reasons, but the smallest ones are most susceptible to this fate. They are replaced by other comet discoveries at large \(N_j\) where the larger nuclei are sampled. Thus with increasing \(N_j\) there should be a tendency for the observed sample of comets to concentrate on larger nuclei, to the effect that the intrinsic decrease of \(A\) is practically cancelled out. We shall return to this selection effect in the next subsection.

The only conclusions possible from brightness data seem to be those based on fading rates of individual comets. In spite of the above-mentioned problems, a few short-period comets are presently considered to fade at a measurable rate during \(-10\) revolutions. The most notable case is that of P/Encke, for which Kresak (1965, 1974) finds a fading rate of about 1 mag. per century. This means that its remaining lifetime might be estimated at a few hundred revolutions, which is in good agreement with the above-mentioned estimate of 500 revolutions for the typical total lifetime of short-period comets. However, extrapolating backwards one finds from the lack of ancient observations (Whipple and Hamid, 1972) and the long time probably required for transfer into the present orbit that even this modest fading rate is considerably higher than the average one. This conclusion will be further substantiated below. Comet Encke may survive longer than most other comets, but this is not surprising in view of its small perihelion distance. However, if the dust coverage model is considered (on the other hand it would be somewhat surprising from the point of view of the mass loss model).

A significant hint regarding the behaviour during short time spans is that in a number of cases, decelerating encounters with Jupiter (i.e., reduction of the perihelion distance) might have been followed by an increase of activity lasting for a few revolutions (Kresak, 1986). Apparently, if this can be confirmed, we have a verification of the decrease of \(B\) with \(N_j\) predicted by the dust coverage model.

### 3.2.3 Evolution of Nongravitational Effects

Nongravitational parameters are listed in Harsden's (1986) catalogue of cometary orbits for a large number of short-period comets. The \(A\) parameters are by far the most reliable ones (Harsden 1974), measuring essentially the delay or advance at perihelion passage (Rickman, 1986). Nonetheless, they are no direct measures of the nongravitational accelerations but depend on several other unknown or variable quantities as well: e.g., the perihelion asymmetries of the gas production curves, and the spin rates and spin axis orientations of the nuclei (Rickman et al., 1987).

Therefore, the observed evolution of \(A\) for individual comets can be used to construct precessional models for the individual nuclei (Sekanina, 1986 and references therein), but they give practically no information about the evolution of the "absolute" acceleration \(A\). Apparently this is true whatever timescale one considers. However, the statistical correlation of \(A\) with \(N_j\) may be investigated, since individual patterns of precession or light curve evolution may then cancel out. Indeed the result of such an analysis (Rickman et al., 1987) is a very clear decrease of \(A\) with \(N_j\), by a factor two from the first three revolutions to those \(-10\) revolutions later or by a factor five with respect to those more than \(30\) revolutions later.

Again one may see this as a verification of the dust coverage model. However, it is difficult to draw quantitative conclusions owing to the above-mentioned observational selection effect. Since the observed sample is expected to concentrate on larger nuclei \((\rho)\), and hence the absolute brightness and nongravitational acceleration, decreases markedly within a short time span (\(<10\) revolutions) following a major decrease of perihelion distance. However, it would be dangerous to extrapolate this behaviour to the scale of the whole cometary lifetime. Even though dust coverage seems to be the process typically at work during short time intervals, this is no guarantee against the ultimate fate of many comets being governed by mass consumption.

Let us briefly discuss the application of the dust coverage model to Encke's comet as an individual case of special interest. Some properties tentatively inferred for the Encke nucleus are listed in table 2. There are now quite a few observations suggesting a low albedo typical of cometary nuclei (Birkett et al., 1987; Banner et al., 1987 and references therein; see also Rickman et al., 1987). Thus it appears

**Table 2:** The Nucleus of Comet P/Encke

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly non-spherical, slowly spinning</td>
<td>1 km</td>
</tr>
<tr>
<td>Typical photometric cross-section</td>
<td>1 km</td>
</tr>
<tr>
<td>If albedo 0.03, then geom. cross-sect.</td>
<td>33 km</td>
</tr>
<tr>
<td>Thus volume:</td>
<td>100 km</td>
</tr>
<tr>
<td>Maximum free-sublimating cross-section</td>
<td>1.3 km</td>
</tr>
<tr>
<td>Thus free-sublimating percentage</td>
<td>(&lt; 4%)</td>
</tr>
<tr>
<td>Mass:</td>
<td>2.5 10^{13} kg</td>
</tr>
<tr>
<td>Thus mean density:</td>
<td>-0.2 g/cm</td>
</tr>
<tr>
<td>Mass loss per apparition:</td>
<td>1 10^{10} kg</td>
</tr>
<tr>
<td>Thus relative mass loss:</td>
<td>0.04 %</td>
</tr>
</tbody>
</table>
likely that the average geometric cross-section of the Encke nucleus is ~ 30 km$^2$. It is not yet possible to estimate accurately the free-sublimating area of this nucleus, but a free-sublimating fraction \( \xi \approx 5\% \) is indicated by the results of several different investigations (Sekanina, 1986b; Jewitt and Meech, 1987; Rickman et al., 1987).

From the results by Rickman et al. (1987) it appears that the nongravitational effects on the orbital motion of comet Encke arises to a large extent from the perihelion asymmetry of the gas production curve, and accordingly the mass of the nucleus is fairly well determined in spite of uncertainties concerning the rotational and thermal properties. The value implied agrees with the mass of a prolate spheroid of average cross-section 30 km$^2$ if the density is ~0.2 g/cm$^3$. The free-sublimating area then amounts to -2000 times the present mass loss per apparition.

We are thus faced with the following set of observational data:
1) The perihelion distance (q = 0.34 AU) is remarkably low.
2) The orbital evolution is at present very slow, since the low aphelion distance (q = 4.1 AU) implies gravitational decoupling from Jupiter.
3) The nucleus is basically inert; probably dust-covered at least 95%.
4) The present relative mass loss per apparition is only ~1/2000.
5) The comet seems to fade by about one magnitude per century.

The first conclusion to be drawn from this is that the present rate of fading is far too high to be explained by mass loss (items 4 and 5). Obviously, also in view of item 3, gradual dust coverage is implied. In fact the fading rate is in good agreement with the above conclusion from the correlation of \( \langle A \rangle \) with \( N_j \). However, we immediately face a problem if the present fading rate, interpreted by means of dust coverage, is extrapolated into the future. Capture of the comet into an orbit with the present perihelion distance would then necessarily have occurred no more than 300-400 years ago, and this appears to conflict with item 2.

Furthermore, it appears difficult to explain how a comet with such a low perihelion distance (item 1) could be subject to dust coverage at about the same rates a typical Jupiter family comet with q ~ 1.5 AU. Thus it appears more reasonable to conclude that the present fading rate is not typical for the secular evolution of Encke's comet. As a consequence of this, a slow capture process into the present orbit can be assumed to the effect that the comet has spent a large number of revolutions with small q. Thus a large number of revolutions can be expected for the past evolution too, and it is not unreasonable to estimate a total life-time of several thousand revolutions in agreement with the relative mass loss rate.

It remains an open question whether the fate of Encke's comet is to shrink and eventually disintegrate or whether the small percentage of free-sublimating area will be covered by refractory material at an average rate much lower than the present one, so that the comet turns into an Apollo asteroid. Let us finally note that the same uncertainty holds for Halley's comet (another one of low perihelion distance) since the estimated relative mass loss (see above) indicates ~300 remaining apparitions, which is no larger than the number expected for the past evolution based on estimates of the capture time scale (Carusi et al., 1987) or the mass of the Halley meteor streams (Mcintosh and Hajduk, 1983; Hughes, 1985).

4. END STATES; CONCLUDING REMARKS

Of course the two scenarios discussed in the previous section lead to very different end states: in the mass loss model essentially nothing (a meteor stream which in general does not intersect the orbit of the Earth), and in the dust coverage model an asteroidal object of cometary origin (extinct comet). Observations of "asteroids in cometary orbits" (Barn and Rickman, 1985) may hence yield clues to the relative importance of the two scenarios. This issue was reviewed by Rickman (1985) and the tentative conclusion has not changed: a large percentage of typical Jupiter-family comets develop into asteroidal objects. These objects are apparently dust-covered icy nuclei rather than silicate cores left behind after total consumption of the ice. The possibly conflicting evidence found above for comets Encke and Halley is naturally explained by the low perihelion distances of these comets which may render secular mantle growth very inefficient. In this context it would of course be interesting to know whether 3200 Phaeton, the parent body of the Geminids (Whipple, 1983), is of asteroidal or cometary origin (Davies, 1985). If it is an extinct comet, then obviously dust choking can indeed occur even at very small perihelion distance.

A word of caution is, however, necessary. According to present-day understanding the sublimation-driven dust mantles should be very thin (perhaps only of centimeter-thickness) so that they are very easily pierced by impacting interplanetary particles of even minor size, and such impacts may occur quite frequently (Fernández, 1981). Indeed, observational evidence tells us only that there appear to be some objects identifiable as at least temporarily extinct comets. A continuation of Fernández' work in estimating collisional lifetime with the particular purpose of finding the typical time scale for rejuvenation of cometary activity is called for. We may be dealing with a population of semi-extinct cometary nuclei of which some have been observed as asteroids such as 944 Hidalgo or 3322 1983 SA, some as low- or intermittent-activity comets such as P/Arden-Rigaux or P/Neujmin 1, and perhaps some only as unconfirmed cometary objects either lost or later classified as asteroids.

Finally it should be stressed that we are still far from a real understanding of cometary evolution, and even when present evidence seems to favour one particular scenario, this evidence is rarely secure enough for us to be confident about the conclusion. This of course means that a lot of interesting work, some of which has been hinted at above, remains to be done!

Acknowledgement. I am very much indebted to my younger colleagues Per Magnusson and Mats Lindgren who wrote whose help manuscript could not have been prepared in time. Discussions with dr. L. Krešák (SFAV, Bratislava) are also gratefully acknowledged. This work was supported by the Svedich-Czechoslovak academy exchange programme.

REFERENCES
Rickman: I took this value from the papers by Klinger and Bar-Nun.
Shulman: The characteristic time at 150 K is only 10 s and it is about 10 hours at 100 K. We need a cosmogenic time-scale of 10 hours. 
Rickman: You have the mass-loss of P/Halley. The mass-loss depends very much on the mass limits of the particles considered. To what upper mass-limit do you refer your above mass loss value?
Rickman: The estimate of 3 x 10^{11} kg is based on the assumption that the total dust mass loss is about one half of the total gas mass loss. This would imply that the upper mass limit of ejected grains is of the order of 1 g on the average. But I would of course expect that the instantaneous value of the limiting mass varies in the course of the apparition.

**DISCUSSION**

**Fechtig**: Weissman has discussed a strong dependency of the pristinity of cometary nuclei on the location of their formation. Do you agree with this opinion?

**Rickman**: Yes, I think that e.g. comets supposed to have formed in the Jupiter-Saturn region may have started out in a less pristine state due to the energetic accretion process. But I should emphasize that I think the present-day pristinity of comets depends to a large extent on their dynamical evolutionary history as well.

**Babadzhanov**: You find that the density of Halley's and Encke's comet nuclei is about 0.2 g/cm^3. But what about the density of the dust grains in your comet model?

**Rickman**: The density of 0.2 g/cm^3 is not directly coupled to any particular comet model as far as the dust is concerned. However, I believe that a comet nucleus with such a low density must be gorgous over a wide range of scales. In particular, it appears that a density of about 1 g/cm^3 for cm-sized or larger dust grains is not compatible with the inferred bulk density of 0.2 g/cm^3.

**Fechtig**: Disregard of the phenomena you discussed are dependent on cometary mass-loss estimates. Can you cite any indirect evidence coming e.g. from non-gravitational forces that could place an upper limit to cometary mass-loss?

**Rickman**: As far as the non-gravitational effect is concerned, the answer is no, since this depends only upon the gaseous mass loss. However, from lifetime arguments using evidence for the previous existence of the comet this may be possible (see comment to Crib's paper in T5-2).

**Shulman**: Why do you think that the crystallization goes on at 150 K only? It is well-known from the physics of vitreous state that it takes place under arbitrary temperature.
almost simultaneously initiated under an entirely different set of conditions, depending on the site where the process took place. Thus, it can not be excluded that there are at least two populations of comets distinguished by their dynamical characteristics as well as by the chemical and structural properties. One population consists of undifferentiated bodies formed in a cold environment at a distance at least 10 AU from the Sun. Dynamically said, comets belong exclusively to the "new" comets of the classical comet cloud. The other population of comets has a combined "high and low" temperature history and dynamically originates from the inner part of a cometary cloud extended up to 10 AU. These comets might be more compact and less fragile and most of them were precursors of such type of small bodies as Apollo asteroids, Ingrid-Strickland Stream or comet-like P/Encke. Such a scenario does not require any exotic mechanism and may be a sound basis for a self-consistent theory of the origin of comets.
HALLEY DUST COMPOSITION

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Progress is reported in evaluating the mass spectra of cometary dust grains that have been obtained by impact mass analyzers flown onboard the Giotto and Vega spacecrafts. Statistical analysis of about 5000 spectra transmitted to the Earth in the more compressed modes 1-3 demonstrates that the mean elemental composition is similar to that of C1 carbonaceous chondrites with the exception of the light elements C, H, O, and N which nearly the solar composition. The isotopic ratios do not differ from solar system values. Five classes of particles are suggested: 1) with dominant Mg-Si element group, 2) with dominant CHON abundances, 3) composites of classes 1 and 2, 4) grains rich in carbon, 5) grains rich in iron and sulphur.

1. Introduction

The chemical compositions, masses, and densities of dust grains in Halley's coma can be deduced from the data obtained by the impact mass spectrometers flown on board the spacecrafts Giotto and Vega 1,2. All three experiments (PIA and PUMA 1,2) are impact ionization time-of-flight (TOF) mass spectrometers of very similar construction (Fig. 1). Their detailed description is given by Kissel (1986). More than 5000 mass spectra of dust grains were transmitted from all three instruments. The aim of this paper is to report further progress in the evaluation of the data and to give a brief overview on the composition of cometary dust.

2. Experimental

Dust grains entering the spectrometer hit a metal target with their high relative velocity (Giotto: 69 km/s; Vega: 78 km/s). The materials and shapes of the targets were as follows:

- **PIA**
  - Thin, slowly moving platinum foil doped with 10% silver.
  - The main source of the mass scale adjustment in spectra of mode 1-3 is the improper operation of **t**2 generator.

- **PUMA 1**
  - Silver plate, corrugated, (the normal line to facets divides the angle between entrance direction and the axis of the first drift tubes into two equal parts of 30 deg)

- **PUMA 2**
  - Thin, slowly moving silver foil

To recognize a dust grain impact, at least one of the following signals had to be triggered - a) the signal from photomultiplier indicating a light flash from the impact point, b) the current pulse occuring on the target and c) the signal from the acceleration grid indicating passage of the ions through the grid. Each of these events can start the time measurement but a coincidence of three events makes the trigger more reliable. The threshold levels of triggering signals were switched between two values differing by a factor of 100 and thus the instrument operated in high or low sensitivity mode.

The clock supplies the square of time elapsed since triggering and hence it should be proportional to the mass of ions at the end of the path through the TOF spectrometer. Positive ions released from the impact site are accelerated by the potential difference between the target and the grid and are directed to the first drift-tube. After completing the 1 m path through the drift tubes and reflector, the ions are detected at the multiplier. The output signal of the multiplier is a logarithmic measure of the ion current.

Time-of-flight spectra were registered in the following modes:

- **mode 0** Output signal from multiplier is sampled with a frequency of 15 MHz, the interval between two samples being 66.7 ns. No time information was transmitted. Spectra are not selected according to quality.

- **mode 1** Same as mode 2, but also ion current minima were sampled.

- **mode 2** Same as mode 3, time samples were created in intervals of 1.06 us.

- **mode 3** Time (**t**2) and multiplier output are sampled (digitized and stored) for each ion current maximum. If no maximum occurs within 8.5 us a time sample was created.

The effective mass resolution in the mode 0 spectra is better than 1 amu as is the case in the more compressed spectra if recognizable peaks of major elements are present. In about 10% PUMA 1 mode 1-3 spectra the absence of strong peaks does not allow to correctly adjust the mass scale. The uncertainty of the peak position, which cannot be assigned to any element at first glance, is generally greater for masses above 56. Also in well defined spectra the uncertainty still remains to be about 1 amu.

In the PUMA instruments the transmittance of the spectrometer was regularly switched between two modes with different ion energy windows: low energy window (0 to 50 eV) resulting in so called "long" spectra and high energy window (0 to 140-190 eV) giving "short" spectra. Substantial differences of instrumental transmivitvity between long and short modes are mainly for light elements. They are discussed in detail by Kissel and Krueger (1987a).

The main source of the mass scale adjustment in spectra of mode 1-3 is the improper operation of **t**2 generator and the subsequent digitisation. It has now been corrected by recognizing some regularities in the **t**2-values. The spectra most influenced by the jitter in **t**2 generator are those of PUMA 1, but on...
the other hand they contain probably less biased values of amplitudes (digitized output from multiplier) than PIA spectra. Data from PUMA 2 are still being recovered from effects of the power supply drop.

3. Isotopic, elemental, and chemical composition

The peaks corresponding to major elements are well recognizable in spectra of mode 0-3, both from PUMA 1 and PIA. The uncompressed spectra also show peaks of less abundant isotopes of major elements, which correspond to their normal abundances. The isotopic composition derived from PUMA 1 spectra mode 0 was discussed in detail elsewhere (Jessberger et al., 1987, Sole et al., 1987). Some typical peak patterns in the corrected mode 1-3 spectra allow the isotopic identification of C, Mg, Si, S, and Fe. The isotopic ratios of the elements are mostly compatible with solar system values (Tab. 1), though the apparent $^{12}$C/$^{13}$C ratios cover a remarkably wide range. The spectra with high energy window (PIA and PUMA 1 short) rather closely reflect the solar isotopic ratios and therefore the contributions of multiply ionized atoms or of molecular ions are negligible, at least at mass numbers corresponding to the isotopes, e.g. 24, 25, 26, 28, 29, 32, 34, 54, 56. On the other hand, some spectra with many peaks of probable molecular origin (mainly PUMA 1 long) show large variations in ratios like 24/25 which varies from 4 to 100.

A large portion of cometary solid grains contains two main components: "silicates" consisting of Si, Mg and heavier elements, and "organics" made out of light elements CHON. The plot of Mg vs. Si ion abundances shows a clear correlation of both elements suggesting that they belong to the same kind of material. On the other hand, there is only a weak correlation between the Si and C abundances (Fig. 3). Apart from the hydrogen content which cannot be estimated precisely in long mode spectra, the main variation among individual grains is in the abundance of oxygen. The ion abundances of O/Si and O/C correlate less than e.g. Mg and Si.

Both components, the silicate rich and the CHON rich grains, differ also in the density which is 0.1-0.3 g/cm$^3$ for the "organic" grains and 0.5-3 g/cm$^3$ for the "silicate" grains which we believe is proportional to the content of iron. The masses of mineral particles are generally higher between 10$^{+14}$ g and 10$^{+12}$ g while organic grains have densities 10$^{+(-14)}$ g or less. The selection rules according to which the spectra were transmitted probably suppressed small particles with few peaks and consequently the frequency of these grains may be underestimated.

Fig. 2 shows mean "short" and "long" spectra derived from PUMA 1 mode 3 data. There spectra are mainly of class 7, i.e. they were triggered by 2 or 3 coincidences and generally contain many peaks. With the exception of mode 0 spectra about 3% of all others reveal only few peaks and there is no such spectrum transmitted during close approach.

The averaging procedure was applied to 1194 mode 3 PUMA 1 spectra, separately for long and short modes, to show an example of mean composition. After the correction for $t^2$-values, the amplitudes $N$ were converted to ion numbers by $10^{N/DL}$ with decade-length DL set to be 25. The sum of the ion numbers over all spectra, divided by the number of spectra, was converted to the logarithms and subsequently the envelope curve was drawn.

Anorganic component

The abundances of heavier elements (Mg etc.) may be consistently inferred both from long and short spectra. Within a factor of 2 the silicate composition is similar to that of CI chondrites (Fig. 4). The data do not yet allow to estimate mineral structures. Water molecule cluster Ag+H$_2$O is found at masses 125 and 127 indicating possible presence of water also in the grains. The abundances of light elements are solar rather than that of CI chondrites.
Fig. 2a The mean PUMA 1 mode 3 spectrum - long operational mode

Fig. 2b The mean PUMA 1 mode 3 spectrum - short operational mode

Fig. 3a Mg/Si ion ratio normalized to carbon (PUMA 1 mode 3 long spectra)

Fig. 3b Mg/Si ion ratio normalized to carbon (PUMA 1 mode 3 short spectra)
Organic component

As it can be seen in the uncompressed spectra only, two types of spectral features may be distinguished:

1. relatively broad profiles where peaks match the integer mass numbers. They are usually assigned to atomic ions.
2. Less frequent narrow profiles that sometimes do not fit any integer mass number even if other peaks corresponding to elements are correctly placed on the scale. These narrow peaks cannot be directly assigned to atomic ions since they occur also at higher masses (above 56).

According to the theory of ion formation processes during the particle impact (Kissel and Krueger, 1987a), some molecules can be released from the grain surfaces by desorption. The initial energy spread of molecular ions should be lower than that of atomic ions. This is consistent with the higher frequency of such peaks in long mode spectra. For example, peaks at masses 41-42, 46-47, 71-72, 79-81, 89-91 coincide with some molecular peaks found in PUMA 1 mode 0 spectra by Kissel and Krueger (1987b) who discuss the probable composition of the molecular species.

3. Conclusion

On the basis of compressed mass spectra the elemental ion abundances were evaluated. The following five classes of cometary grains are suggested (in parentheses their approximate frequency is given):

1. "silicate" grains consisting mainly of Mg, Si (Fe) (10%)  
2. "organic" grains consisting mainly of light elements - CHON (6%)  
3. composite particles of material from class 1 and 2 (70%)  
4. "pure carbon" particles C, (H) (12%)  
5. "trollite" particles Fe, S (10%)

The actual population of classes 2, 4, 5 may have been underestimated because of the selection procedure before data transmission to Earth and also due to the procedure of mass-scale adjustment during spectra evaluation. Some spectra (completing the classification to 100%) are difficult to interpret because major element peaks are not recognizable.

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DISCUSSION

Ibadov: What can you say about the existence of multicharged ions (due to high-velocity collisions of cometary dust particles with interplanetary bodies considered theoretically in our work)?

Jeschberger: Multicharged anionium ions were detected.
ON THE PHENOMENON OF ANOMALOUS DISTRIBUTION OF METAL ATOM EMISSION IN COMETARY HEADS

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The theory of cooling of cometary dust by a gas outflowing from the nucleus is developed and used for explaining the anomalous distribution of sodium atom emission in the head of Comet Mrkos 1957 d. The results obtained indicate the universal character of the phenomenon of anomalous distribution of metal atom emissions, including the Na I lines, in the heads of bright comets and the possibility of condensation of a cometary gas (H₂O, CO₂ etc.) in the nearnuclear region.

Key words: comets - metal atom emissions - anomalous distribution

1. Introduction

Spectral observations of Comet Mrkos 1957d by 5-meter Palomar telescope lead to the detection of the phenomenon of anomalous distribution of sodium atom emission, namely the displacement of intensity maximum of sodium atom emission toward the Sun to the distance nearly 2000 km from the cometary nucleus (Greenstein, 1958; Greenstein and Arpigny, 1962).

Present approaches to the interpretation of anomalous distribution of sodium atom emission in the head of Comet Mrkos 1957d may be divided in three classes: 1) optical, accepting the optical thickness of the cometary coma in sodium lines to be very large (> 1) for nearnuclear region (i.e. for the cometocentric distance r < 2000 km) (Greenstein and Arpigny, 1962). We have to note, however, that such assumption is done without corresponding physical basis, namely without analysis of the possibility of intensive release of sodium atoms in the nearnuclear region; 2) kinematical, starting from the optical thin coma and attempting to explain the anomalous maximum of brightness as a classical Bessel-Bredikhin envelope of Na-atoms which were ejected from the nucleus towards the Sun and then, under the action of light pressure, move in opposite direction (Wurm, 1963). However, such explanation, as known (Solovolov, 1966, p. 78), is contradictory to Sokhman's law, since in this case the maximum of brightness have to be near the nucleus at arbitrary distribution of initial velocities of ejection; 3) atomic approach, proceeding from the view point that sources of Na-atoms are, together with the nucleus, also dust particles in the head of a comet (on the role of dust particles as a main supplier of metal atoms observed in the cometary atmospheres see e.g. Dalsemme, 1982; Donn and Rahe, 1982; Levin, 1964; Wyckoff, 1982). The anomaly in the distribution of sodium intensity may be explained if the presence of a small-moving dust envelope - a dusty halo - in the cometary atmosphere is supposed. However both the absence of well expressed correlation between the intensity of Na-spectrum and continuous spectrum and the gradual fall of intensity in the first 3000-8000 km from the nucleus towards the Sun observed do not allow us to confirm it with fully confidence. Thus, the question on the mechanisms causing the anomalous distribution of Na I emission in the head of Comet Mrkos 1957d remains open.

2. Cometary Dust Cooling by Gas Outflowing from a Nucleus as the Cause of the Anomaly

The temperature of dust particles of cometary atmospheres T determines the rate of their evaporation and therefore the concentration of metal atoms in the cometary atmospheres, so that the spatial inhomogeneity of T = T(r) may cause the corresponding inhomogeneous distribution of metal atoms in the cometary heads.

Conglomerate model of cometary nuclei as a mixture of ices and solid particles now generally accepted allows highly intensive ejection of gases (H₂O, CO₂ etc.) from nuclei (see e.g. Biermann and Treftz, 1964; Liller, 1960; Sagdeev et al., 1986; Whipple, 1950), especially at small heliocentric distances r < 0.7 - 1 AU, i.e. where in comet spectra lines of metals (Na, Fe, Ni etc.) are usually observed (see e.g. Greenstein, 1958; Greenstein and Arpigny, 1962; Levin, 1964; Oppenheimer, 1980; Preston, 1967).

Along with this, according to recent calculations (Bisikalo and Strel'nikov, 1965; Grodzialer, 1984; Marconi and Mendié, 1983; Marov and Shematovich, 1987; Shima, 1976), the temperature of cometary gas T(r) has a deep minimum (T min = 10 - 50 K) at r = 10⁹ - 10¹⁰ km because of a strong self-cooling of gas due to its expansion and intensive 15- radiation of cometary molecules and, within the whole inner coma (r < 10⁴ - 10⁵ km) not exceeds the temperature of subliming surface of a nucleus of both the telescopic and the bright comets; this temperature is always low by themselves: T < 200 - 300 K (see e.g. Sagdeev et al., 1986). In this connection we shall consider the establishment of the temperature of a dust particle ejected from the nucleus into the coma with an initial temperature T₀ taking into account the cooling effect of criogenic gas flow.

The equation of heating of a cometary dust particle by solar radiation may be written in the form

\[ R \alpha d q dt = cm dT + 4 \pi a^2 L (\sigma T^4 - T_0^4) dt + 6 \pi a^2 q n_0 (\varepsilon T - T_0) dt, \]

where \( R \) is the radius of a dust particle, \( \alpha \) is the integral absorption coefficient of solar radiation, \( \sigma \) the density of which, \( q \) vary depending on the distance of r, \( \varepsilon = q_0 R^{-2} \) (with \( q_0 = 1.36 \times 10^6 \) erg cm⁻² s⁻¹ is the solar constant); \( c, m \) and \( q_0 \) are the specific heat capacity, the
mass and the integral heat radiation coefficient of the grain; \( \varepsilon \) is the Stephan-Boltzmann constant; \( k \) is the Boltzmann constant; \( \chi \) is the accommodation coefficient of molecules of gas at the grain surface; \( n_c \) is the number density of gaseous molecules; \( \dot{V} \) is their thermal velocity, corresponding to temperature \( T_{\text{cr}} \), the left-hand side of Eq. (1) is the radiation energy absorbed by a particle, and the terms on the right-hand side concern the heating of the particle, its radiational and molecular cooling.

Eq. (1) is completed by the expression for the distribution of number density of molecules in the flow escaping from the nucleus

\[
\frac{d}{\dot{V}} \frac{n_g(r, R)}{dT} = \frac{4}{\mu_g \chi} k T^2 \varepsilon - 6 \alpha \dot{V} n_g \frac{\dot{V}}{V} (\omega - T_g)\]

where \( \dot{V} \) is the observed dust production rate in \( \dot{V}_d / \dot{V} \), \( \mu_g \) is the mean molecular weight, \( k_B \) is the Boltzmann constant, and \( (\omega - T_g) \) is the total area of the nucleus, \( r_c \) is the nuclear radius.

Eq. (1) is reduced to nonlinear integral equation

\[
\int \frac{d\tau}{\dot{V}} = \int V d\tau = \int_0^T n_g(r, R) \frac{dT}{d\tau} = \frac{4}{\mu_g \chi} k T^2 \varepsilon - 6 \alpha \dot{V} n_g \frac{\dot{V}}{V} (\omega - T_g)\]

which we consider for two regimes:

1. The radiational cooling is essentially greater than the molecular one (weak comets) Then Eq. (4) with quasi-constant coefficients (the velocity of grains outflowing from the nucleus \( V_g \), the density of gaseous \( n_g \) etc. weakly change with \( r \)) corresponds to quasistationary temperature \( T_\text{cr} \), as seen from (5), is the length of the relaxation zone, where the heating of the particle from an initial temperature \( T_\text{cr} \) up to quasistationary temperature \( T_\text{cr} \) takes place, namely \( T(1 = 1) = 0.9 T_\text{cr} \), and

\[
T_\text{cr} = \left[ (\chi + 4 \alpha \dot{V})/4 \chi \right]^{1/4} = \left[ (\varepsilon / \chi) \right]^{1/4} \left[ T_\text{cr} \right]^{1/4} \cdot
\]

From Eq. (1) with using (2) \( T(r) \) may be found for various values of \( r/r_c \). As the result we have \( T(r = 3 r_c) = 0.9 T_\text{cr} \), i.e. at the zone \( r = 3 r_c \) the temperature of particles is almost equal to the limiting maximal temperature corresponding to quasistationary vacuum regime.

Scheme of temperature distribution in cometary coma is shown in Fig. 1. - dust temperature in atmospheres of weak comets, i.e. at "vacuum" approximation; 2 - dust temperature in coma of bright comets, i.e. at conditions of cooling effect of a gas (numerical values of parameters as in the text below).
The vapour pressure of condensed substances depends on the temperature exponentially. So at cometary conditions the maximal release of metal atoms will be at the zone of cometocentric distances of $r_{\text{max}} = 3r_{\text{cr}}$. Using Eqs. (3), (7), (10) and (11) we have
\begin{equation}
(13) \quad r_{\text{max}} = 2.5 \left( \frac{a \sqrt{\mu g^2 r^{2/3}}}{\varepsilon^{3/4} \varepsilon^{1/4} \kappa_g \kappa_b} \right)^{1/2}.
\end{equation}

Accepting for Comet Krkos 1957d during 17 - 19 August, when $R = 0.559 - 0.599$ AU, the values of $\dot{M}_d(R = 0.6 \text{ AU}) = 10^3 \text{g/s}$ (Liller, 1960), $\varepsilon = 1$, $V_c = 10^5 \text{cm/s}$, $a = \varepsilon = 0.1$ (metallic particles), $\mu = 0.1$, $\kappa_g = 20$, $\kappa_b = 0.1$ by (13) we obtain $r_{\text{max}} = 1200$ km. This value is near to the date of the spectral observations (Greenstein, 1958; Greenstein and Arpigny, 1962). Along with that for Comet Halley 1982i near the perihelion by (13) we get $r_{\text{max}} = 100$ km. Because of gas-dust matter is ejected mainly towards the Sun, the maximum of metal atom emissions, including the sodium lines, have to be observed mainly in the Sun direction. Moreover, the application of relations (7) and (12) to icy and quartz type particles ($a \approx 0.01$) indicates the possibility of condensation of gases H$_2$O, CO$_2$ type in the nearnuclear region and the amplification by such way the dusty component of comets (Ibadov, 1983). These questions are in the stage of developing (see also Yamamoto and Ashihara, 1985).

3. Conclusions

The account of cooling effect of cometary grains by gaseous flow from nucleus allows to explain most naturally the phenomenon of anomalous distribution of sodium atom emission in the head of Comet Krkos 1957d and indicates the universal character of the phenomenon of anomalous distribution of metal atom emissions in the heads of bright comets. This effect may be revealed in the cometary atmosphere by spectral observations with sufficiently high spatial resolution - of the order of 10 - 1000 km. The resolutions ~10 - 100 km may be realized, probably, during missions to comets. The condensation of cometary gases is possible in the nearnuclear region.

The author is grateful to Prof. O.V. Dobrovolsky for useful discussions.

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DISCUSSION

Crifo J.F.: Your proposed explanation for Na anomalies being due to release from grains may be appropriate, but the way of your computation differs from known hydrodynamic methods (Finson and Probst, Marconi and Mendis, Combos, Heilmich and Keller and myself). What conditions do exist for cometary dust cooling by gas?

S. Ibadov: Results of hydrodynamic approach to gas-dust motion are used in our equations. Cometary dust cooling by cryogenic gas outflowing from a nucleus occurs at sufficiently high number density of molecules, \( n \geq 10^{11} \text{ cm}^{-3} \), which corresponds also to local thermodynamic equilibrium state, the flow is not free molecular on a scale of coma. Number density of dust particles \( n \geq 10^7 \text{ cm}^{-3} \). So, for bright comets (for their near-nuclear region) new solution of the problem of cometary dust temperature appears, which corresponds, particularly, to Na anomaly.
LABORATORY INVESTIGATION OF THERMAL CONDUCTIVITY OF DUST CRUST MODELS ON THE ICE COMET NUCLEI SURFACES

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For the purpose of studying the thermal conductivity of comet ice nucleus surfaces dust crust we have carried out the laboratory experiments on the cometary nucleus models. The experiments were carried out under the conditions close to those at the heliocentric distances from 1 to 3 A.U. The ice H₂O which contained the particles of quartz, graphite, nickel and organic substances D.L-alanin, D.L-treonin, L-valin has been studied. The dust matrices 5-15 mm in thickness have been formed under the ice sublimation irradiated with a light beam. In most cases the effective thermal conductivity of the matrices which included sublimation products diffused in them is one or two orders less than that of H₂O.

Key words: dust crust - thermal conductivity - ice nucleus - laboratory modelling.

1. INTRODUCTION

The missions of the cosmic apparatuses Vega-1,2 (Ref.1) and those of Giotto (Ref.2) resulted in obtaining the confirmation of the statement that the hardmelting dust crust on the surface of the nuclei of some part of periodical comets, the Halley Comet included (Ref.3, 4). The dust crust plays an essential role in the evolution of a cometary nucleus and other cometary phenomena and the study of the crust properties is of great importance today.

The authors of the paper presented for several years have been carrying out a number of laboratory experiments aimed at the study of physical, mechanical and thermal properties of the ice nuclei cometary surface of mineral crust. Some of the results obtained on the physical and mechanical properties of dust matrices models and organic substance matrices are given in (Ref.7, 8). Here we are going to discuss the results of the experiments devoted to the thermal conductivity of these matrices (Ref.10).

2. THE MODEL OF COMETARY NUCLEUS AND THE EXPERIMENTAL METHODS

As an ice nucleus base in our experiments we have taken H₂O the presence of which in cometary nuclei was obtained such indirect evidence. During the cosmic apparatus mission to Halley Comet (Ref.1, 2). As hardmelting impurity we used the dust particles of quartz (1-2 µ in size), graphite (10-100 µ), nickel (1-2 µ) and organic substances D.L-alanin, D.L-treonin, L-valin. The laboratory experiments (such as Ref.7, 8) showed that under the certain conditions porous matrices can be formed on the surface from the dust particles and organic substances under the sublimation of such nucleus model. The possibility that impurities chosen by us exist has been repeatedly mentioned in literature but other versions of hardmelting constituent of cometary nucleus are quite possible in principle, although as the experimental results showed, it doesn't play the substantial part when solving the given problem.

The experimental methods were due to the concrete aim of the experiment, that is, it was necessary to obtain the mineral matrices of necessary thickness in the process of sublimation of conglomerate ice cometary nucleus under the conditions very close to cometary ones and to determine the coefficient of this matrix thermal conductivity. The samples of cometary nucleus models under investigation were prepared at the atmospheric pressure in the special cuvettes by freezing the mixture of distilled water and impurities in the vapour of liquid nitrogen. In the course of experiments several variations of construction and the cuvette material and cylindrical cuvettes made from phthoroplast and cork have been found most successful. The greatest number of experiments has been carried out on the samples prepared in the cuvettes made from phthoroplast and cork whose thermal conductivity (0.04 w/(m·K)) is less than that of sand. The diagram of a typical cuvette is shown in Fig.1. The diameter of investigated models used to be 30 mm, their thickness ranged between 20-25 mm. At least 4 thermocouples were mounted in the cuvette and the maximum error when measuring the temperature of a model did not exceed 1°K.

Figure 1. Vacuum chamber for imitation of cometary conditions. 1 - chamber, 2 - cryostat, 3 - glass window, 4 - cuvette with nucleus models.
The experiments have been carried out in the high vacuum and low temperature chamber (Fig.1) that made it possible to keep a relatively uniform temperature field around the investigated models. According to the experimental methods already prepared nucleus models after having been cooled to the temperature of 77°K were put in the chamber, that had been pumped out until the pressure was 10^{-6} Torr and at the same time had been cooled by liquid nitrogen through the cryostat mounted inside the chamber. The solar photon radiation imitation has been done by the superhigh pressure mercury lamp and the irradiation of the models surface by visible light was done outside the chamber through the glass window after the limited vacuum in the chamber and equibalanced temperature of nuclear models had been reached.

The specific feature of the experiment was that in order to obtain reliable results about the coefficient of thermal conductivity it was necessary to produce matrices with 5 mm and greater thickness under sublimation process. The little thickness was responsible for the error when determining the irradiated parameter due to the errors made in the determination of the thickness itself h and temperature T. To produce such matrices is specific matter. The matrices are being destroyed by the quasicontinuous flow of sublimated gas, when the light beam incident on the surface of a model is highly energetic while under the conditions of low energy the time of the experiment increases. For instance, under the experimental conditions, equivalent to the conditions at 3.0 A.U. to obtain dust matrices 5 mm thick it takes 20-30 days of continuous irradiation of the models by light when the dust concentration in the model is average. The substantial increase of dust concentration in the model makes it unreal. We in our experiments inclined to the choice of optimal version. In most cases we imitated the conditions of location cometary nucleus at 1-2 A.U. which made it possible to obtain matrices 5-15 mm thick during approximately 10 days of the experiment (that is 200-250 irradiation hours by light beam) when the impurity concentration in the model was real. Throughout all the experimental time the temperature of the nuclear model was measured in 4 points of volume. To avoid the direct incidence of light the outside thermocouple was mounted at the depth of 1 mm from the model's surface.

3. RESULTS

In the course of experimenting on different variations of cometary nuclear model the numerical experimental data about the temperature due to the matrix thickness and its character have been obtained by us. Fig.2 shows the characteristic graph of nuclear model temperature dependence on the time t. Throughout the whole experiment the energy quantity of light beam incident on the surface of model remains constant. The change of temperature takes place on the surface of a model with the formation and growth of a matrix, the sharp increase in temperature coincides with the release of a given thermocouple from ice. The distance between the thermocouples ΔX and temperature gradient being known we can find the coefficient of thermal conductivity of a matrix λ as

\[ \lambda = \frac{\varepsilon Q \Delta X}{S \Delta T} \]

where \( \varepsilon \) is the coefficient of the absorption of the model surface, Q is the energy of light beam incident on the surface and S is the area of model's surface. The numerical value of \( \varepsilon \) for each variation of nuclear model has been determined experimentally. The value of \( Q \) has been determined by direct measurement of light beam energy.

It is known, that in the porous dust layer the heat can be transferred through the contacts between dust particles, gas molecules in pores, by light irradiation. We have studied the effective thermal conductivity of a matrix when all 3 canals of heat transfer could be active. The part of experimental results determining the effective coefficient of thermal conductivity is given in the Table 1.

The result of our determination of the thermal conductivity of ice H₂O (3.6 w M⁻¹ K⁻¹) coefficient coincides with the data obtained by other authors (Ref.9) by various methods and confirms the right choice of the experimental method.

The thermal conductivity of matrices (Table 1) proved to be one or two orders less than that of ice H₂O and is close to that of very soft snow (0.12 w M⁻¹ K⁻¹) or sand and depends on the porosity of a matrix. We didn't find the substantial dependence λeff on the matrices material. From the data presented in the table it follows that in the course of calculations of the thermal regime of ice comet nuclei possessing the hardmelting surface crust one can take the coefficient of thermal conductivity of this porous crust as \( \sim 10^{-4} \) w M⁻¹ K⁻¹.

Figure 2. Nucleus models temperature from time dependence. The time of release of thermocouple from ice indicated by hand.
Table 1. Effective thermal conductivity of dust crust models on the ice comet nuclei surfaces

<table>
<thead>
<tr>
<th>Matrices models</th>
<th>Middle temperature of matrix, °K</th>
<th>Porous, %</th>
<th>Density ρ, kg m⁻³</th>
<th>Thermal conductivity λ_eff, W m⁻¹ K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite particles</td>
<td>235</td>
<td>80</td>
<td>460</td>
<td>7x10⁻²</td>
</tr>
<tr>
<td>Quartz particles</td>
<td>160</td>
<td>40</td>
<td>1360</td>
<td>8x10⁻²</td>
</tr>
<tr>
<td>Nickel particles</td>
<td>220</td>
<td>60</td>
<td>3100</td>
<td>10x10⁻²</td>
</tr>
<tr>
<td>DL-Alanin</td>
<td>250</td>
<td>98</td>
<td>24</td>
<td>6x10⁻²</td>
</tr>
<tr>
<td>DL-Treonin</td>
<td>240</td>
<td>97</td>
<td>35</td>
<td>6x10⁻²</td>
</tr>
<tr>
<td>L-Valin</td>
<td>240</td>
<td>97</td>
<td>36</td>
<td>6x10⁻²</td>
</tr>
</tbody>
</table>

4. REFERENCES

ARE COMETARY DUST MASS LOSS RATES DEDUCED FROM OPTICAL EMISSIONS RELIABLE?

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ABSTRACT

We present additional evidence in support of our previous work (Crifo, 1987 b-c) in which, from theoretical fits to Comet Halley near -to far- infrared emissions, based on the in-situ flyby probes data, we estimated that the comet was losing half or more of its mass under the form of large (> 1 gram) grains of small (0.3 g cm~3) density. We confirm that the comet dust-to-gas mass loss rate ratio lies somewhere between the values 0.80 and 18.6, with a best estimate at 3.46. We discuss this result in the context of the general agreement that comets loose less than half of their total mass loss in dust, and this dominantly at very small grain sizes. We trace this agreement back to overconfidence placed in a model size distribution which inherently excludes substantial mass loss in large grains without appropriate experimental justification.

I. Introductory definitions and remarks

We will characterize the size distribution of the dust released by the nucleus either by the grain radius normalized differential distribution \( n_0(a) \), or by the grain mass normalized integral (or "cumulative") distribution \( \gamma_0(>m) \). Due to the mass dependence of the velocities \( V \) imparted to the grains by the escaping gas, the corresponding distributions in the coma \( \eta(a) \) and \( \gamma(>m) \) differ from \( n_0 \) and \( \gamma_0 \) (Hanner, 1984, Green et al., 1987). If power laws hold in some size range:

\[
\eta_0(a) \propto a^{-\alpha_0} ; \quad \eta(a) \propto a^{-\alpha} ; \\
\gamma_0(>m) \propto m^{-\beta_0} ; \quad \gamma(>m) \propto m^{-\beta}
\]

then one has the relations

\[
N_0 - 1 = \frac{d \ln V(a)}{d \ln \alpha(\alpha_0)} ; \quad \frac{N - N_0}{3} = \frac{d \ln \gamma(>m)}{d \ln \beta(\beta_0)} \quad \text{(1)}
\]

\[
3(\alpha - \alpha_0) = N - N_0 = u = \frac{d \ln \gamma(>m)}{d \ln m} \quad \text{(2)}
\]

\( V(a) \) may depend upon the size distribution and therefore must be determined self consistently by hydrodynamic methods. Computations of these kind (Gombosi, 1986 ; Crifo, 1987b) give the value \( u \approx 0.167 - 0.18 \) for sufficiently large masses.

At a given heliocentric distance, \( r_o \), grains can be dragged away from the nucleus only up to a maximum radius \( A_{max} (r_o) \) to which corresponds a maximum mass \( m(A_{max}) \) (Whipple, 1950). However, only observations can tell us whether all possible sizes are indeed represented in the coma, thus we also define \( A \), the radius of the maximum mass \( m(A) \) really present in the coma.

Finally, a spacecraft flying through the coma at a relative velocity much greater than all \( V(a) \) may be hit by grains only up to a certain radius \( A_{max} \) with mass \( m(A_{max}) \) defined by a collection probability equal to 1 during the whole flyby.

We generally(*) have

\[
A_{max} \leq A \leq A_{max} ; \quad m(A_{max}) \leq m(A) \leq (m(A))
\]

Computations of the total optical emission involve integration of \( \eta(a) \) to \( A \), and computations of the total dust mass loss rate involve integration of \( n_0(a) \) to \( A \). Therefore, if \( A \) is indeed large and if power law applies, we see that (Green et al., 1987):

1 The optical signal is bound (independent of \( A \)) if \( \alpha > 0.67 (N_0 > 3.54) \).
2 The dust mass loss is bound if \( \alpha > 0.82 (N_0 > 4) \).

This already tells us that optical sounding alone cannot give unambiguous results concerning the mass loss, unless \( \alpha \) is reliably known, and particularly at large masses. Confidence to be placed in such results should be proportional to the confidence one can have in the value of \( \alpha \) especially near \( m(A) \).

* Following a strong and sudden decrease in the gas production rate, \( A \) could exceed \( A_{max} \)

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II Theoretical determination of \( m(A_{\text{max}}) \) for comet Halley at \( r_0 = 0.9 \text{ AU} \)

Equating the surface gravitational force and the gas drag force, one gets the following simple formula (Whipple, 1950, Gombosi, 1986):

\[
m(A_{\text{max}}) = \frac{1}{2} \frac{M_e}{\rho} \frac{V_e}{g} A_{\text{max}} \quad (3)
\]

where \( M_e \) is the gas mass loss rate, \( \rho \) the surface gravity, \( V_e \) the initial gas outflow velocity, \( A \) the maximum cross section of the particle, and \( g \) the corresponding drag coefficient at the surface. Exploitation of this formula is simple only for spherical grains on a spherical comet. Still, in this case, considerable care must be taken to assess properly the gas initial conditions (see Crifo, 1987a) and \( C_\alpha \). We have discovered that, there is a secular expression for \( C_\alpha \), used by Whipple, Gombosi, and others, lead to values of \( A_{\text{max}} \) much greater than the gas collision freepath (Crifo, 1987a). Therefore they are not applicable! We have therefore used for \( C_\alpha \) more general (but approximate) expressions valid for spheres in the slip and transition regime at any Mach number. The resulting \( m(A_{\text{max}}) \)--accurate to 60 \%-- is shown as a function of the assumed grain density on figure 1.

Since in real the grains are not spherical, there is a much larger uncertainty resulting from the shape dependence of \( C_\alpha \). Consequently, we estimate that, for \( r = 0.9 \text{ AU} \) and at \( \rho = 0.3 \text{ g cm}^{-3} \), the range of possible values for \( m(A_{\text{max}}) \) is:

\[
5 \times 10^3 \text{ gram} \leq m(A_{\text{max}}) \leq 3 \times 10^5 \text{ gram}
\]

Thus, in this range the exponent \( \alpha \) must increase, representing a smooth cutoff. We ignore this effect in our computations and take for \( m(A_{\text{max}}) \) the nominal value given by figure 1.

III Cometary dust mass loss estimates prior to comet Halley flybys: values, or lower limits?

Three different methods were in use: (1) dynamical analysis of a few comet tails (Finson and Probstain, 1968); (2) model fits to the scattered light continuum (Newburn and Spirad, 1985); (3) model fits to the IR continuum (e.g. Hanner, 1984).

The first method allows derivation of \( \eta(a) \) on a restricted size range (a < 100 \text{ \mu}m for antitails, i.e. in this case grains of a few milligrams << \( m(A_{\text{max}}) \)). The derived values of \( N_\alpha \) on the "large" (milligram) size side were 4.0 to 4.5 (Sekanina, 1980), i.e. marginally above the value required for the optical emission and loss rate to be bound.

The two other methods imply a theoretical computation of the coma emission, and therefore have to specify a dust size distribution. Following the suggestion of Hanner (1983) the following formula was used:

\[
\eta(a) \propto (1 - \alpha_0 / a)^{N_\alpha} (\alpha_0 / a)^N \quad (4)
\]

with typical parameter values \( \alpha_0 \approx 0.1 \mu\text{m} \), \( M = 20-30 \), and, most importantly, \( N = 3.7 \). It was found to give "a very satisfactory fit to visual and infrared data" (Newburn and Spirad, 1985, see also Crifo, 1982, where a slightly different version of \( \eta(a) \) is used). The value for \( N \) was justified by the tail analysis data.

It is indeed surprising that this value for \( N \) is just marginally that needed to insure bound flux and mass loss. Realizing this, Hanner (1984) looked for additional justifications based on analysis of observed IR emissions between 3 and 20 \mu m in wavelength. She finds that indeed the condition \( N \geq 3.5 \) is required. And the "notes (that this condition) indicates that the mass is concentrated toward the small grains". However, for this statement to be correct one must demonstrate that the IR signal really requires the algebraic expression (4) for \( \eta(a) \) over the seven decades in mass where the tail observations do not place such constraints. From formula (4), however, we see that \( \eta(a) \) is proportional to \( a^{-N_\alpha} \) as soon as \( a \) exceeds a few times \( (M/N) \alpha_0 \), i.e. a few microns (<< 10^{-6} \text{ gram}). Owing to the convergence of the flux integral, the fluxes computed by Hanner (1984) are due to grains below 10^{-7} \text{ gram}, and the constraint on \( N \) applies to grains in the range 10^{-9}--10^{-7} \text{ gram}. In other words, the assumption that (4) holds up to \( m(A_{\text{max}}) \) implies that the emission is due to grains below 10^{-7} \text{ gram}.

To constrain the production rate of grains beyond this mass, it would have been necessary to vary the shape of \( \eta(a) \) (e.g. the exponent \( N \)) above 10^{-7} \text{ gram} and to look at the effect on the infrared emission. We have done this (Crifo, 1987b, c and this work) and found that indeed values of \( N \) as small as 2.0 above 10^{-5} \text{ gram} lead to remarkable quantitative fits to comet Halley infrared spectra from 1 to 60 \mu m in wavelengths!

Following this evidence, we propose to consider all dust-to-gas production rate ratios based on formula (4) or equivalent ones as "lower limits derived using the contingent assumption that a unique power law grain size distribution applies over the mass range 10^{-9}--10^{-5} \text{ gram}". These "lower limits" were found in the range 0.05 to 0.3 with exceptional extreme values 0.004 and 0.85.
IV. Comet Halley observations

IV.1 In-situ dust analysis

The "Vega" and "Giotto" in-situ detectors revealed \( \zeta(>m) \) distributions of the form \( m^{-2.5} \) with \( a_2 = 0.8 - 1.0 \) over the mass interval \( 10^{-2} - 10^{-3} \) gram (Mazets et al., 1986, Mc Donnell et al., 1986 and 1987), corresponding to \( \Phi_0 \) values \( 3.94 - 4.5 \), confirming the results recalled in section III. Between \( 10^{-3} \) and \( 10^{-2} \) gram, however, the \( \zeta(>m) \) data reveal a softening of \( \zeta(>m) \), being there in the interval 0.33 - 0.59 (Mc Donnell et al., 1987). Also a difference of one order of magnitude was found between the "Vega 2" and "Giotto" implied dust production rates, in the mass interval \( 10^{-15} \) to \( 10^{-7} \) gram, raising the question of which one of these results applies to average coma conditions.

IV.2 Giotto spacecraft deceleration

The Doppler shift of the "Giotto" transmitter revealed the interception of a total mass \( M_p = 1.95 \) gram (Edenhofer et al., 1986), while scaling the detector fluences to the spacecraft cross-section indicates a mass \( M_0 = 0.235 \) gram only (Mc Donnell et al., 1986). The "missing mass" must be looked for in grains above the detector's upper limit of 5.7 milligram. Evidence for the impact of a large (0.4 gram) grain is provided by the spacecraft destabilization just before closest approach (Grüner et al., 1987). Assuming that the "soft" \( \zeta(>m) \) found above \( 10^{-5} \) gram, holds to about 1 gram, Me Donnell et al., 1986). It remained to investigate whether this unorthodox assumption was compatible with optical data, in view of Hanner (1984) considerations discussed in III.

IV.3 Coma infrared emissions

We have invested a large effort in analyzing the compatibility between remote and in-situ observations of comet Halley dust (Crifo, 1987 b-c and this presentation). We computed the infrared emissions from P/Halley's coma using a distribution \( \Phi(\alpha) \) inspired by Mc Donnell et al. (1986-1987) work, i.e.

1) below \( 10^{-5} \) gram it is either derived from the Giotto fluences ("G" case) or from the "Vega 2" fluences ("V" case) or from whichever of these fluences gives the largest production rate at a given mass ("up (G, V)" case, or upper envelope).

2) above \( 10^{-5} \) gram, in the "V" case is the power law extrapolation of the Vega 2 data (i.e. \( a_2 = 0.9 \)), and in the "G" or "up (G, V)" cases it is a power law with index \( a_2 \) that can assume any value between 0.35 and 0.55 (##)

Extremely simple formulae were used to relate the fluences to the size distributions, to compute \( M_0 \), and to compute the optical fluxes at Earth (see Crifo, 1987b). It is estimated that the computed optical fluxes are accurate to \( \pm 50\% \) in absolute values, following neglect of the complex pattern of dust emission from the nucleus revealed by the flyby cameras.

It was assumed that, at each mass, the dust was equally partitioned between dirty (\( k_w = 0.03 \)) amorphous olivine and amorphous carbon. The grain density \( \rho(m) \) was left as an unknown function to derive from the fits, together with \( a_2 \) and the maximum mass \( m(A) \).

In Crifo (1987 b-c), the dust outflow velocities were derived self-consistently from a 79-fluid model taking into account \( \zeta(>m) \). The maximum mass accessible in the model was 100 gram. The computed velocities were found in general agreement with those of Gombosi (1986) who also has a broad size spectrum, but uses a small (0.3) dust-to-gas mass production rate ratio. This agreement illustrates the fact that the velocities are weakly affected by dust loads concentrated in large grains.

In this presentation we include recent results obtained with an improved model using 87 fluids and giving therefore access to the maximum ejectable mass at 0.9 AU, i.e. \( \sim 30 \) kilogram.

The optical computations were performed with extreme care, using as far as possible realistic complex indexes of refraction and recombining the resulting grain temperatures (see Crifo, 1987 b-c). Mie scattering and absorption efficiencies were computed using the new Complex Angular Momentum method (Nussenzveig, 1983).

In compiling experimental data, we interpolated between experimental points, ignoring deliberately the experimenters' approximate "fits".

Our computations are strictly deterministic, i.e. do not include ad hoc scaling factors. We require them to reproduce (1) the shape of the continuum, particularly in the "trough" between scattered light and thermal emission, and at long wavelengths ; (2) the absolute value of the continuum ; (3) the observed emission features in the so-called "silicate" emission region.

## We here indicate that the results presented in Crifo 1987c are computed with \( a_2 = 0.35 \), value not given in the text of that paper.
IV.3.1 Fits to emissions at \( r_o > 1 \) AU

We performed theoretical fits to data acquired over the wavelength interval 1 to 65 \( \mu m \), at \( r_o = 1.28 \) AU before perihelion, by Tokunaga et al. (1986), Campins et al. (1986), Herter et al. (1986) and Glaccum et al. (1986), and to data extending from 1.5 \( \mu m \) to 30 \( \mu m \), at \( r_o = 1.15 \) AU post-perihelion, taken from Gehrz et al. (1986), Green et al. (1986), and Knacke et al. (1986).

Our conclusions were the following:

(1) Best fits are always obtained assuming \( \rho (m) = c^G = 0.3 \) g cm\(^{-2} \) (to \( \pm 50 \% \)). In particular, the "ESA WD" proposition of a decrease in density with increasing size is excluded.

(2) The "Pure Giotto" ("G") distribution cannot account for the observed emissions, because it implies a ratio of large to small grains such that no emission feature is visible.

(3) A choice of "sup (G, V)" distributions provide equally good best fits. They differ by their combinations of (\( \alpha_2 \), \( m(A) \)) values, as indicated in Table I. We note that maximum value of \( \alpha_2 \) is found, implying a maximum value for \( m(a) \) (3.04). This conclusion is exactly opposite to the one of Hanner (1984), illustrating the correctness of our analysis made in section III, that her conclusions apply to \( a_1 \) only.

(4) Considering the \( \pm 50 \% \) uncertainty in the absolute values of our model fluxes, the range of acceptable parameters broadens considerably. In particular, the "pure Vega" ("V") distribution becomes acceptable. This illustrates the poor capabilities of the optical sizing technique by itself, already discussed in Crifo (1987 c).

(5) We find that the \( M^0 \) requirement implies \( \alpha_2 = 0.425 \pm 0.012 \). This value lies in the middle of the interval 0.33-0.59 indicated by the Giotto data. Mc Donnell et al. (1987), from the same requirement, compute \( \alpha_2 \approx 0.50 \). This difference probably can be traced back to our neglect of "momentum enhancement factors" in computing \( M_0 \). Momentarily, one can take the interval 0.5-0.412 as bracketing the uncertainty range for \( \alpha_2 \). Figure 2 shows fits of pre-perihelion data with \( \alpha_2 = 0.425 \) and various \( m(A) \), from which everyone can form his own conviction concerning the choice of the best fit value \( m(A) = 100 \) gram.

(6) The computed dust-to-gas mass loss rate ratio corresponding to this best fit is \( r = 3.46 \). However, keeping the value \( \alpha_2 = 0.425 \) constant, the mentioned \( \pm 50 \% \) uncertainty in absolute flux computations makes it possible to use, instead of the best \( m(A) = 100 \) gram the lower value \( m(A) = (m_{\text{max}}) = 2 \) gram. In this case \( r = 0.80 \). It is as well just possible to use the highest possible value \( m(A) \), for which \( r = 18.6 \). Until additional experimental data provides new constraints, this must be taken as the present range of uncertainty concerning \( r \).

(7) Beyond 1 AU, the "silicate" emission features present in the 10-20 \( \mu m \) region are "small" or even absent, which makes the fits relatively easy because a relatively large ratio of large to small grains is allowed. However, as demonstrated by our similar work on comet Kohoutek at small heliocentric distances (Crifo, 1987 c), difficulties may be expected when observations reveal "large" emission features. Therefore we have extended our earlier work to include observations of comet Halley at smaller heliocentric distances.

IV.3.2 Fits to emissions at \( r_o = 0.9 \) AU

Figure 3 shows spectra of comet Halley at \( r_o = 0.9 \) AU from the Sun obtained pre-perihelion by Tokunaga et al. (1986), and post-perihelion by Hayward et al. (1987) and Hanner et al. (1987). In their publications, the authors show a continuum which is not a measurement result. Thus, we have retained only their data points and interpolated linearly in-between. We have indicated by a dotted line the approximate expected shape of the continuum in the "trough' region, based on the Tokunaga data, in order to avoid misinterpretations.

On figure 4 A-B-C-D we reproduce the two post perihelion experimental curves and a choice of model computations. Figures 4A and 4B show the predicted spectra obtained with the "V" distribution and with "sup (G, V)" at \( \alpha_2 = 0.425 \), assuming various values for \( m(A) \). The continuum fit looks good, as far as one can judge considering the small number of data points. But the contrast of the computed "silicate" emission features looks weaker than in the data. Therefore, we show on figures 4C and 4D the contribution to the computed fluxes of the dirty olivine component of our model. In other words, if we assumed that the dust was 100% dirty amorphous olivine, the corresponding computed fluxes would be those of figure 4C and 4D, multiplied by 2. This produces suitably contrasted features--but, now, the continuum below 8 \( \mu m \) is not correctly reproduced. It has long since been shown (see e.g. Crifo, 1982) that only a mixture of dielectric and absorbing grains can lead to correct continuum fits. Replacing half of the dielectric grains by absorbing ones, however, dims the emission features significantly.

Since changes in the silicate/carbon ratio have opposite effects on the fits to the
continuum and to the emission features, we do not think that such a mixture represents the real situation in comet Halley's coma. It should be understood only as a computational necessity in the absence of an adequate formalism making it possible to compute the emissions from real grains which, we believe, must include both silicates and absorbers (Crifo, 1987c). The fractionation between silicate and carbon grains does not appear physically plausible and is not well supported by the in-situ grain elemental composition data (Jessberger et al., 1986). It is reasonable to think that the complex refractive index of inhomogeneous aggregates mimics the absorbing signatures of each of its components, i.e. resemble that of silicates in the 10-20 μm region, and that of carbonaceous matter elsewhere. A two-component model approximates this situation but not perfectly.

For the same reason, no matter how good our fits are, they should not be used to claim that precisely amorphous carbon and/or dirty amorphous olivine exist in Halley's coma! Any other absorber and/or dielectric with rest-strahlen bands may provide eventually as convincing fits.

It may be appropriate to make a final remark. The contrast of the emission features fluctuates at a given r (Gehrz and Ney, 1986) and perhaps also their shape (Hanner et al., 1987). Perfect fitting of one given observation is therefore meaningless. Contrast fluctuations have been tentatively attributed to changes in the silicate/carbon content (Gehrz and Ney, 1988). We have indicated above why we dont believe that the coma is a mixture of well contrasted dust grains. Instead, these fluctuations could be well reproduced by minor fluctuation, in the ratio of large to small grain coma contents associated with the time modulation of the emission. But since our model is stationary it does not include such effects.

V. Conclusion

Quantitative analysis of a large set of optical observations of comet Halley provides vigorous support to the suggestion by Mc Donnell et al. (1986, 1987) that comet Halley dust size distribution flattens at masses above 10^{-5} gram and extends beyond the gram range. While the small mass exponent α2 is near 0.35, the optimum value of the large mass exponent α2 is near 0.425. With these values, the fits to the comet emissions considered in this work indicate that the dust-to-gas mass loss rate ratio in the comet is at least 0.80 and at most 18.6, with a best estimate at 3.46. The upper limit is set by the optical data and by the hydrodynamics, and the lower limit by the Giotto deceleration requirement. These values are well outside the range of ratios determined in any other comet. This is not interpreted as an indication that comet Halley is atypical, but as an indication that all previous determinations have a common built-in artefact. It can indeed be identified as the artificial assumption that a size distribution, based on a restricted set of observations concerning only small and intermediate mass grains holds as well for large and very large grains. Accordingly all estimates based on this assumption should be considered as lower limits only.

<table>
<thead>
<tr>
<th>Assumed α2</th>
<th>Best fit m(A), mm</th>
<th>r, gram</th>
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<tr>
<td>0.35</td>
<td>3</td>
<td>1.78</td>
</tr>
<tr>
<td>0.40</td>
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<td>2.64</td>
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<tr>
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<tr>
<td>0.50</td>
<td>NONE</td>
<td>-</td>
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</table>

Table I

For each assumed value α2, the requested value of m(A) is indicated, and the resulting dust-to-gas mass loss rate ratio, r. The computed values of M allow the final choice of α2.

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Newburn, H.L. and Spinrad, H.: 1985, Astron. J. 90, 12, 2591-2608

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(**) Proceedings of the International Colloquium on the Similarity and Diversity of comets, Bruxelles, April 1987

FIGURES
Please notice that the Figures are given in the order 1, 3, 2, 4.

Q = 7. x 10^29 gsec^-1
M = 2.4 x 10^13 gram
R = 4. x 10^5 cm
\( \Omega \) = \( \pi \)

FIGURE 1. Maximum mass of a spherical grain ejectable from P/Halley at 0.9 AU from Sun. \( M \) is the assumed nucleus mass, \( Q \) the water molecule loss rate, and \( R \) the distance from nucleus center of mass. For non-spherical grains, \( M(\alpha) \) can differ from the above values by up to \( \pm \) or \( \pm \times 8 \).
FIGURE 2. Model fits to P/Halley emissions at 1.25 AU from Sun, Pre-Perihelion. Curve A is the composite of experimental data (see text). Curves B are computed with 'sup(G,V)' and \( q_2 = 0.425 \) and \( m(A) \) as indicated.

FIGURE 4 A

FIGURE 4 B

FIGURE 4 C

FIGURE 4 D

FIGURE 4 E

FIGURE 4 F

FIGURE 3.

Model fits to P/Halley emissions at 0.9 AU Post-Perihelion. Curves A and B are identical to those of Figure 4, and curves C are model computations. Figures 4A and 4C are computed with the 'V' distribution, and 4B and 4D with 'sup(G,V)' using \( q_2 = 0.425 \) and \( m(A) = 1, 10, 10^2, 10^3, 10^4 \) gram. Figures 4C and 4D are the total emission (Carbon + Olivine), Figures 4A and 4B the Olivine component only (50% of the mass).
**DISCUSSION**

**Hajduk:** I agree entirely that the dust/gas ratio, including contribution of large particles, should be increased by about one order of magnitude, in comparison with the values currently quoted. But is it possible to interpret your $M_d/M$ values of 0.8 to 19 as corresponding to the nucleus density of 0.3 g/cm$^3$?  

**Crifo:** My optical data require a dust density of 0.3 g/cm$^3$ at 50%. If the ratio $M_d/M$ is large, then this will also be the nucleus density. But I find impossible to determine $M_d/M$ better than within the limits 0.8 to 19. This uncertainty follows from the ignorance of what is the maximum mass in the coma (it is somewhere between a few grams and a few tens of kilograms). Also we do not know for sure what is the slope of the dust distribution beyond a few grams, but, as my table indicates, this is a less severe source of uncertainty than the previous one.

**Rickman:** Some constraint on the dust production rate might come from the value of $M/\Delta M$ (the ratio of the nucleus mass to the total mass loss per apparition). Let us estimate the mass at $M = 1 \times 10^{14}$ kg and the gaseous mass loss at $\Delta M = 2 \times 10^{11}$ kg. Then from your minimum value of $M/M_n = 0.8$, one finds $\Delta M = 3.6 \times 10^{11}$ kg and $M/\Delta M = 24$. But from your maximum value of $M/M_n = 20$, the result is $\Delta M = 4.2 \times 10^{12}$ kg and $M/\Delta M = 24$. Even though $M/\Delta M$ is not a reliable estimate of the remaining lifetime, I think the latter value appears uncomfortably low, since orbital studies indicate that the comet has already passed at least many hundred revolutions in its present orbit.  

**Crifo:** It would indeed be surprising that $M_d/M$ were precisely equal to the upper limit 20. We know nothing about the dust size distribution above 1 g, and, as I mentioned, the slope exponent is at least expected to increase above 1 kg due to size dispersion effects. On the other hand, it would also be surprising that $M_d/M$ were equal to 0.8, because this would imply that the dust distribution has a sharp cutoff just precisely at the maximum that Giotto could intercept!
IMAGE PROCESSING OF VEGA-TV OBSERVATIONS

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Abstract. Methods of processing of VEGA-TV observations of the nucleus of P/Halley and derived scientific results are summarized. The existence of lineamentary surface structures is interpreted as an indication for boundary zones between km-sized blocks, building the cometary nucleus. The consequences for cometary origin are investigated.

1. Observations and interpretation
Two of the VEGA-2 close encounter images of P/Halley are most appropriate for studying properties of the cometary nucleus. The images were taken 1.5 sec before and 98.7 sec after closest encounter from distances of 8.045 km and 11.060 km respectively. The angle spacecraft - nucleus - sun was for these two images 28.4° and -23.0° respectively, so the dayside of the cometary nucleus with its great activity became visible (in contrast to GIOTTO images). Consequently, the nucleus is visible only through the scattered light from the near-nucleus dust, which is most intense above the "active" dayside.

Special image processing software has been used to identify shape of and structures on the cometary nucleus. The main steps of this processing have been described by Möhlmann et al. (1986). They refer to image restoration, noise-reduction, gradient- and Laplace filtering and overlay-techniques with false-colour images.

The essential result can be seen in Fig. 1, giving a synthetic image of the nucleus and its direct surroundings. The outer white line indicates limb and terminator. Dark lines (which are brighter in reality) are indications for lineamentary surface structures. They are described directly with Fig. 2, as they were derived from the above mentioned two images. The comparison with lineamentary structures, as they were derived from Sekanina and Larson (1986) by tracing the foot-points of jets from observations, made in 1910, is given with Fig. 3, where the "open window" indicates that region of the nucleus, which has been seen by the VEGA-spacecrafts during close encounter.

These linear structures are interpreted as an indication for a block-structure of cometary nuclei. The contact zones between these km-sized building blocks are the brighter zones of enhanced cometary activity, as it is inferred by the "active" lineamentary zones.

2. Origin cometary nuclei
The above described model of a cometary nucleus, made of relatively large km-sized blocks with contact zones between them, can be understood as an indication for a soft accretional growth of cometary nuclei from these building blocks ("cometesimals"). It is especially the fact that these cometesimals survived this growth by impacts and it is the existence of the relatively thin impact-caused and impact-modified contact zones, which indicates that these accretional impacts were "soft". Consequently, the impact velocities should have been remarkably small. A maximum value for this velocity can be estimated by comparing the total binding energy of a km-sized cometesimal and its kinetic energy which is released by the impact process.

The cohesive strength \( \tau \) of binding of cometary matter has been shown to be the order of \( \tau = 10^4 \) Pa (Wetherill and Re Velle, 1982). If the total binding energy \( E_b = \frac{4}{3} \pi f \rho t \\rho \) of a cometesimal of density \( \rho \) equals the kinetic energy \( E_k = \frac{1}{2} m v^2 \) of the impact with relative velocity \( v \), the impacting cometesimal would be destroyed totally. Consequently it follows for the real impact velocity \( v_1 \)

\[
v_1 < \left( \frac{2 E_b}{\rho} \right)^{1/2}
\]

With a density \( \rho = 0.2 \) g cm\(^{-3}\) \( = 2 \times 10^2 \) kg/cm\(^3\) follows

\[
v_1 < 10 \text{ m/sec.}
\]

This is a remarkably low impact velocity. This value can be modified if it is assumed that the kinetic energy can be transformed partially also into heat. But very proba-
bely this process is very ineffective. This should be due to the relatively low cohesive strength of cometary matter.

Difference velocities of the order of some meters per second (or less) are typical for regions, far out in the Solar system, with distances exceeding 10^3 AU.

But there is the number density too small to have a sufficient number of collisions.

On the other side, this range of velocities should be typical for the growth-phase of planetesimals from first-generation planetesimals, formed from an unstable thin preplanetary disk, as it has been described by Goldreich and Ward (1973). The contraction of these clusters of fragments depends on the rate at which gas drag damps, and on their internal rotational and kinetic energies.

The internal velocities in this cluster can be estimated by

\[ v_i^2 \approx \gamma \sum \lambda \sim \Lambda \mu m^2/\sec^2 \]

(\( \gamma = 6.674 \times 10^{-11} \text{m}^3/\text{kg} \text{s}^2 \), typical scale for instability). The resulting conclusion is, that cometary nuclei were formed in the outer planetary system by the Goldreich-Ward-mechanism for the formation of planetesimals. Comets are the planetesimals of the outer planetary system.

References

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**DISCUSSION**

**Napier:** Safronov finds that the mutual impact velocities in a dynamically relaxed system are determined by the largest bodies present and are of the order of their surface escape velocities. If there were 50 to 100 km comets around during the coagulation of Halley's comet then the \( \sim \) km-sized bodies should have been colliding at substantially more than \( \sim \) km/s. Conversely, impacts at less than \( \sim \) km/s imply that the majority of accreting bodies would be much less than 1 km in diameter.

**Möhlmann:** The internal relative velocity in a cluster of the "first generation" planetesimals can be estimated from the potential energy of this cluster, leading to \( \sqrt{\frac{2}{GM}} \) (\( G = 6.674 \times 10^{-11} \) \( \text{m}^3/\text{kg sec}^2 \), \( M = 10^9 \) \( \text{kg/m}^2 \) and \( \sim 10^6 \) m - according to Goldreich and Ward). Equating this with the internal kinetic energy, this leads to the order of magnitude \( \sim 1 \) m/s for the relative velocities. This value coincides indeed with the escape velocity from 1 km to 10 km sized "building blocks". Greater bodies probably did not exist in this cluster.

**Grön:** You cannot emphasize too much the similarity of your line and structures with the results Sekanina got in analysis of the 1910 observations, because these results were obtained by assuming a fixed spin axis. But Sekanina himself points out that recent observations indicate a much more complex rotational state of the nucleus (Nature 325, p. 326). Therefore, at least the combinations of loci of sources which were observed at different times cannot be correct. The map published by Sekanina (AJ 92, p. 462) must be incorrect, because observations covered a time span of several months.

**Möhlmann:** I agree with you, but I think that Sekanina's rotation period (and the axis of rotation he used) were not too wrong. So, the topological character of his results should survive, when more precise values are used. Consequently, the detailed identification should not be correct, but similarities should remain. This has been assumed in comparing Sekanina's results with those of VEGA-TV image processing.
Numerous spectrograms of Halley's Comet have been taken by the author during October 1985 - May 1986 with the Hissar astronomical observatory 70-cm reflecting telescope AZT-8 and SPN-1 spectrograph giving a dispersion of 160 Å/mm. A two cascade image intensifier with fiber optics and Kodak 103Ag emulsion have been used.

On the basis of four red and near IR spectra taken on 16 December 1985 with 5 to 40 min exposures a set of provisional identifications shown in the Table was given.

Key words: Comet Halley, - IR Spectra, - N₂ molecule

The author expresses his thanks to prof. O.V. Dobrovolsky for helpful discussions.

<table>
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<th>N₂(4-3)</th>
<th>N₂(2-1)</th>
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<tbody>
<tr>
<td>α obs.</td>
<td>8595</td>
<td>8491</td>
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We have taken Halley's spectra using the new spectrograph SPN-1 (flat replica, 600 lines per mm, dispersion 160 Å/mm) attached to the telescope AZT-8 (mirror diameter 70 cm, Cassegrain focus 13 m) of the Hissar observatory.

The spectrograph is equipped with a two cascade intensifier having fiber optics.

First spectrograms were taken during the 16-17 October 1985 night, Preperihelion observations were run till 16 December; that postperihelion from 19 April to 5 May 1986. The observational nights total to 15, the number of spectra received is about 50. The slit width was 5", the spectral range was 6000 - 9000 Å and slightly broadened with ground exposure. This region containing many pure known bands such as the red system of CN, Phillips system of C₂, emissions of H₂O, NH etc. is very interesting.

For express identification we have chosen the spectra, taken on 16 December 1985 totalling to 4 and having different exposure times: 5, 10, 20 and 40 min. Registrogram of the 10-min. exposure spectrum is shown on the Figure. This day the comet showed a strong continuum and many weak emissions.

In the registrogramme middle (at λ 7519 Å) a strong telluric O absorption band is seen.

Other identification are: red CN system bands (2-0, 3-1); C₂-Phillips system bands (2-0, 1-0, and 2-1); C₂ Swan system sequence (av = 2); bands of H₂O (0,5,0; 0,6,0; 0,7,0; 0,8,0; 1,0; 0,0; 0,1) and water steam absorptions at 7200 and 8300 Å. A total of about 200 emission peaks are identified on the 5-min and 10-min exposure spectrograms (see table). Designations of CO emissions were given according to Comovici et al. (1982).

Except the known substances we have identified also H₂ and N₂. These identifications were performed using the spectral tables by Penrose and Caygill (1949) (Russian issue).

Identification of H₂ is the first one made on ground and confirmed (Tentatively) in space: Giotto registered mass-spectrographically the probable presence of N₂, as was stated by Eberhardt et al (1986).

It should be mentioned that Denke et al (1981!) have found in another comet a strong red CN (1-0) emission listed of the C₂ (2-0) feature missing on their spectrograms.

Some distortion of the field of view of our image intensified is not excluded, but a careful examination showed it to be small and not to be leading to misidentification of futures concerned.
<table>
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Registrogramme of Comet Halley spectrum taken on 16 December 1985 with 10 min exposure.

REFERENCES


A second part of the pre-perihelion photoelectric measurements of P/Halley obtained at the Skalnate Pleso Observatory is presented. The observations cover 9 nights from November 8, 1985 to January 5, 1986. A set of focal diaphragms of the following diameters was used: 29.53" , 48.98" , 81.08" , 137.34" and 220.53" . Results of this paper are magnitudes in focal diaphragms in the filters Cont. 365.0 nm, Cont. 484.5 nm, CO , C2, C3 and CN. Coma diameters, photometric parameters and continuum colors are also determined.

1. Observational technique

The photoelectric observations were made with a photoelectric photometer, installed in the Cassegrain focus of the 600/7500 mm reflector at the Skalnate Pleso Observatory. An EMI 6256 B type electron multiplier was used as a radiation detector. The optico-mechanical parts contains a set of focal diaphragms with the following diameters: 29.53" , 48.98" , 81.08" , 137.34" and 220.53" . The diaphragm diameters were measured with the Abbe comparator. Five basic IHW filters and the CO one are installed in the optical part of the photometer. A detailed description of the photoelectric photometer system is published elsewhere (Klocok et al., 1987).

In accordance with the recommendation of the discipline specialist team for photometry and polarimetry net, the observations have been made at the poor atmospheric conditions, too. This must be taken into consideration in the interpretation of the results.

2. Comparison stars and extinction changes

Comparison stars have been chosen from the list recommended by A'Hearn and Vanysek (1984). The magnitudes (listed in Table 1) according to the IHW list of Standard stars (Peierberg, 1985) have only been used for processing the observations.

Table 1

<table>
<thead>
<tr>
<th>HD</th>
<th>Interval used</th>
<th>UC</th>
<th>CN</th>
<th>C2</th>
<th>CO</th>
<th>BC</th>
<th>C2</th>
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<tbody>
<tr>
<td>186427</td>
<td>Whole</td>
<td>7.68</td>
<td>7.96</td>
<td>7.35</td>
<td>7.23</td>
<td>6.50</td>
<td>6.46</td>
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<tr>
<td>25680</td>
<td>Nov 8-16</td>
<td>7.27</td>
<td>7.47</td>
<td>6.99</td>
<td>6.86</td>
<td>6.15</td>
<td>6.09</td>
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<tr>
<td>216667</td>
<td>Dec 22-Jan 5</td>
<td>7.83</td>
<td>7.97</td>
<td>7.57</td>
<td>7.45</td>
<td>6.80</td>
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<tr>
<td>3379</td>
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<td>5.66</td>
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<td>5.66</td>
<td>-</td>
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<td>16908</td>
<td>Whole</td>
<td>4.71</td>
<td>4.68</td>
<td>4.67</td>
<td>4.66</td>
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</table>

For all the nights the extinction coefficients were determined as follows:

Table 2

<table>
<thead>
<tr>
<th>1985/86 Date</th>
<th>k(Cont. 365.0)</th>
<th>k(Cont. 484.5)</th>
<th>k(CO+)</th>
<th>k(C2)</th>
<th>k(CN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 8/9</td>
<td>-</td>
<td>0.400</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nov 11/12</td>
<td>0.627</td>
<td>0.254</td>
<td>0.32</td>
<td>0.160</td>
<td>0.477</td>
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<tr>
<td>Nov 16/17</td>
<td>0.782</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nov 17/18</td>
<td>1.287</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dec 12</td>
<td>0.714</td>
<td>0.696</td>
<td>-</td>
<td>-</td>
<td>0.870</td>
</tr>
<tr>
<td>Dec 13</td>
<td>0.206</td>
<td>0.295</td>
<td>0.750</td>
<td>-</td>
<td>0.396</td>
</tr>
<tr>
<td>Dec 22</td>
<td>0.080</td>
<td>0.540</td>
<td>-</td>
<td>-</td>
<td>0.200</td>
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<tr>
<td>Dec 30</td>
<td>-</td>
<td>0.316</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jan 5</td>
<td>0.604</td>
<td>0.398</td>
<td>0.625</td>
<td>-</td>
<td>0.573</td>
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</table>

mean ± standard error

<table>
<thead>
<tr>
<th>1985/86 Date</th>
<th>k(Cont. 365.0)</th>
<th>k(Cont. 484.5)</th>
<th>k(CO+)</th>
<th>k(C2)</th>
<th>k(CN)</th>
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<td>Nov 8/9</td>
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<td>0.095</td>
<td>0.098</td>
<td>0.025</td>
<td>0.091</td>
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The values of Table (2) show large night to night changes of the extinction. These rapid variations of atmospheric conditions excluded applying the mean value of the coefficient.

3. Coma diameters

The diameter of the coma was measured by means of photoelectric cross-section through the photometric nucleus in the direction of right ascension. It was supposed that the image of the comet was approximately circular. The tail did not contribute to the brightness in the direction of cross-section. The diameter of the coma was measured with the aid of a diurnal motion, by stopping the telescope drive. Each registration was repeated independently several times, in order to eliminate the effects of inaccurate setting on the
The magnitude of the comet due solely to the emission feature alone is then given by

\[ m' = m - 5 \log \Delta \]  

(1)

where \( \Delta \) is the geocentric distance and \( m \) the magnitude at the largest diaphragm.

### Table 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Cont 365.0</th>
<th>Cont 484.5</th>
<th>C0</th>
<th>C2</th>
<th>C3</th>
<th>CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>66 ± 16</td>
<td>123 ± 34</td>
<td>68 ± 3</td>
<td>289 ± 124</td>
<td>190 ± 89</td>
<td>215 ± 49</td>
</tr>
<tr>
<td>Nov 15/16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>165 ± 28</td>
<td>223 ± 56</td>
</tr>
<tr>
<td>Nov 16/17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>197 ± 59</td>
<td></td>
</tr>
<tr>
<td>Nov 17/18</td>
<td>-</td>
<td>127 ± 59</td>
<td>-</td>
<td>-</td>
<td>326 ± 116</td>
<td></td>
</tr>
<tr>
<td>Dec 3/4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>295 ± 9</td>
<td></td>
</tr>
<tr>
<td>Dec 12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>419 ± 26</td>
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</tr>
<tr>
<td>Dec 13</td>
<td>107 ± 6</td>
<td>151 ± 35</td>
<td>-</td>
<td>-</td>
<td>611 ± 92</td>
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</tr>
<tr>
<td>Dec 22</td>
<td>95 ± 27</td>
<td>137 ± 31</td>
<td>-</td>
<td>-</td>
<td>613 ± 36</td>
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</table>

### Table 4

**Continuum 365.0**

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitudes at diaphragms (standard errors in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>12.66 (0.04)</td>
</tr>
<tr>
<td>Nov 16/17</td>
<td>13.02 (0.05)</td>
</tr>
<tr>
<td>Nov 17/18</td>
<td>13.50 (0.15)</td>
</tr>
<tr>
<td>Dec 12</td>
<td>10.26 (0.08)</td>
</tr>
<tr>
<td>Dec 13</td>
<td>10.68 (0.04)</td>
</tr>
<tr>
<td>Dec 22</td>
<td>11.12 (0.07)</td>
</tr>
<tr>
<td>Jan 5</td>
<td>9.14 (0.06)</td>
</tr>
</tbody>
</table>

### Table 5

**Continuum 484.5**

<table>
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<tr>
<th>Date</th>
<th>Magnitudes at diaphragms (standard errors in parentheses)</th>
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<tr>
<td>Nov 5/3</td>
<td>11.73 (0.03)</td>
</tr>
<tr>
<td>Nov 17/18</td>
<td>12.24 (0.02)</td>
</tr>
<tr>
<td>Dec 12</td>
<td>13.05 (0.09)</td>
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<tr>
<td>Dec 13</td>
<td>9.46 (0.01)</td>
</tr>
<tr>
<td>Dec 22</td>
<td>8.35 (0.02)</td>
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<td>Dec 30</td>
<td>6.46 (0.01)</td>
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<tr>
<td>Jan 5</td>
<td>5.46 (0.10)</td>
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### 4.2. Continuum 484.5

The columns in the Table 5 have the same meaning as those of Table 4.

### 4.3. Emission C0^+

To remove the underlying continuum we used the method of A'Hearn (1984). We assumed that the filters for the continuum (365.0 and 484.5) were not contaminated by any emission bands. Let the magnitude at the emission bands be represented by

\[ m_{\text{em}}(\lambda_0) = \lambda + \frac{\lambda_0 - \lambda_0}{\lambda_0 - \lambda_0} m_{\text{em}}(\lambda_0) + \frac{\lambda_2 - \lambda_0}{\lambda_2 - \lambda_0} m_{\text{em}}(\lambda_0) \]  

(2)

where \( \lambda_0 = 426.0 \) nm, \( \lambda_0 = 365.0 \) nm, \( \lambda_2 = 484.5 \) nm.

The average value of \( \lambda \) for 6 solar analogs is \( \lambda_{\text{sun}} = (0.16 \pm 0.03) \) mag.

Then we used \( \overline{X} \) to determine the cometary magnitude \( m_{\text{com}}(\lambda_0) \), which would have been observed in the absence of any emission band:

\[ m_{\text{com}}(\lambda_0) = \overline{X} + \frac{\lambda_0 - \lambda_0}{\lambda_0} m_{\text{com}}(\lambda_0) + \frac{\lambda_2 - \lambda_0}{\lambda_2 - \lambda_0} m_{\text{com}}(\lambda_0) \]  

(3)

The magnitude of the comet due solely to the emission feature alone is then given by
The CO magnitudes calculating according to the equation (4) are listed in Table 6.

### Table 6

<table>
<thead>
<tr>
<th>1985/86 Date</th>
<th>Magnitudes at diaphragms (standard errors in parentheses)</th>
<th>m'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>12.71 (0.09) 11.81 (0.02) 11.70 (0.01) 11.69 (0.01) -</td>
<td>12.18</td>
</tr>
<tr>
<td>Dec 13</td>
<td>-             12.15 (0.01) 11.77 (0.03) 11.35 (0.01) 11.01 (0.01) 11.50</td>
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</tr>
<tr>
<td>Jan 5</td>
<td>10.47 (0.01) - 10.32 (0.01) - 9.20 (0.02) 8.72</td>
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</table>

4.4. Emission C2

\[ \Delta \text{C}_2 = (0.24 \pm 0.02) \text{ mag.} \]

The C2 magnitudes calculating according to the equation (4) are listed in Table 7.

### Table 7

<table>
<thead>
<tr>
<th>1985 Date</th>
<th>Magnitudes at diaphragms (standard errors in parentheses)</th>
<th>m'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>11.30 (0.16) 10.22 (0.06) 9.26 (0.02) 6.34 (0.01) 7.55 (0.01) 7.20</td>
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4.5. Emission C3

\[ \Delta \text{C}_3 = (0.08 \pm 0.02) \text{ mag.} \]

The C3 magnitudes calculating according to the equation (4) are listed in Table 8.

### Table 8

<table>
<thead>
<tr>
<th>1985/86 Date</th>
<th>Magnitudes at diaphragms (standard errors in parentheses)</th>
<th>m'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>12.11 (0.09) 11.03 (0.01) 10.50 (0.02) 9.86 (0.01) 9.51 (0.01) 10.00</td>
<td></td>
</tr>
<tr>
<td>Dec 12</td>
<td>-             9.71 (0.02) 8.66 (0.01) 8.06 (0.02) 7.60 (0.01) 6.14</td>
<td></td>
</tr>
<tr>
<td>Dec 13</td>
<td>-             9.72 (0.01) 9.14 (0.03) 8.57 (0.01) 8.16 (0.01) 6.97</td>
<td></td>
</tr>
<tr>
<td>Dec 22</td>
<td>-             8.29 (0.01) 7.60 (0.01) 6.80 (0.0) 6.32 (0.01) 6.39</td>
<td></td>
</tr>
<tr>
<td>Jan 5</td>
<td>9.77 (0.04) - 7.91 (0.01) - 7.60 (0.01) 7.32</td>
<td></td>
</tr>
</tbody>
</table>

4.6. Emission CN

\[ \Delta \text{CN} = (0.50 \pm 0.02) \text{ mag.} \]

The CN magnitudes calculating according to the equation (4) are listed in Table 9.

### Table 9

<table>
<thead>
<tr>
<th>1985/86 Date</th>
<th>Magnitudes at diaphragms (standard errors in parentheses)</th>
<th>m'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>11.10 (0.05) 10.20 (0.04) 9.32 (0.01) 8.40 (0.01) 7.74 (0.01) 8.23</td>
<td></td>
</tr>
<tr>
<td>Dec 12</td>
<td>-             7.96 (0.03) 7.10 (0.01) 6.19 (0.01) 5.48 (0.01) 6.02</td>
<td></td>
</tr>
<tr>
<td>Dec 13</td>
<td>-             8.27 (0.02) 7.34 (0.02) 6.51 (0.01) 5.79 (0.01) 6.28</td>
<td></td>
</tr>
<tr>
<td>Dec 22</td>
<td>-             6.88 (0.01) 6.24 (0.01) 5.73 (0.01) 5.80</td>
<td></td>
</tr>
<tr>
<td>Jan 5</td>
<td>7.07 (0.01) - 5.16 (0.01) - 4.09 (0.01) 3.61</td>
<td></td>
</tr>
</tbody>
</table>

5. Changes of the brightness

The photometric parameters \( M \) and \( n \), defined by the relation

\[ M = m' - 2.5 \log r \] (5)

where \( r \) is the heliocentric distance and \( m' \) the magnitude reduced to unit geocentric distance (Eq. 1) are listed in Table 10. Coefficient of correlation between the quantities \( m' \) and \( \log r \) is 0.95 - 0.98.

### Table 10

<table>
<thead>
<tr>
<th>Region</th>
<th>( n )</th>
<th>( M ) (mag)</th>
<th>( r ) (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>5.0 ± 0.8</td>
<td>7.84 ± 0.31</td>
<td>1.76-0.94</td>
</tr>
<tr>
<td>C0</td>
<td>5.0 ± 0.4</td>
<td>6.66 ± 0.16</td>
<td>1.81-0.94</td>
</tr>
<tr>
<td>C0</td>
<td>5.1 ± 1.7</td>
<td>9.40 ± 0.68</td>
<td>1.76-0.94</td>
</tr>
<tr>
<td>C0</td>
<td>3.8 ± 0.7</td>
<td>7.55 ± 0.23</td>
<td>1.76-0.94</td>
</tr>
<tr>
<td>C0</td>
<td>6.9 ± 0.7</td>
<td>4.34 ± 0.24</td>
<td>1.76-0.94</td>
</tr>
</tbody>
</table>
6. Continuum colors

The colors of the cometary material can be represented as color excesses (A'Hearn, 1984):

\[ E(U-B) = \left[ m_{\odot}(365.0) - m_{\odot}(484.5) \right] - \left[ m_{\odot}(365.0) - m_{\odot}(484.5) \right] \]

The solar color was taken to be the average color of the solar analogs

\[ m_{\odot}(365.0) - m_{\odot}(484.5) = 1.19 \text{ mag.} \]

Table 11

<table>
<thead>
<tr>
<th>1985/86 Date</th>
<th>B(U-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 11/12</td>
<td>- 0.56 mag.</td>
</tr>
<tr>
<td>Dec 12</td>
<td>+ 0.01</td>
</tr>
<tr>
<td>Dec 13</td>
<td>+ 0.07</td>
</tr>
<tr>
<td>Dec 22</td>
<td>+ 0.33</td>
</tr>
<tr>
<td>Jan 5</td>
<td>- 0.39</td>
</tr>
</tbody>
</table>

7. Conclusions

1. A progressive increase of the brightness caused by approaching of Comet Halley towards the Earth and the Sun is overlapped by sudden outbursts. For example, there was an outburst before December 13, 1985. This outburst was detected as a local maximum of the brightness on both emissions C₂, CH and continuum on December 12. The outburst was confirmed independently by Watanabe et al. (1986) in C₂-emission. Tokunaga et al. (1986) also pointed out that on 12 December the comet was brighter at all wavelengths compared to 13 December. On 12 December the comet had the bluest J-H color.

2. The behaviour of the coma diameters, during the period of observations, shows that with exception of CN-coma, diameters of observed comas did not depend on the heliocentric distance.

3. The photometric exponent only for CN-emission shows that the increase of the brightness was steeper than for continuums.

4. During the whole observing period, practically whole observed brightness of the comet originated in CN-emission.

5. Comparison of the measurements with different focal diameters gives a higher concentration of the brightness C₂ and CO² comas to the brightest point in the coma than in the C₂ and CH comas.

6. In contrast to the J-H and H-K colors (Tokunaga et al., 1986) the U-B color varied considerably during the interval of observations.

6. References


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Long slit Halley comet spectra taken at ESO Observatory after the perihelion have been analyzed. Relative intensity radial profiles along and perpendicular to the sun direction have been obtained for CN (Av=0), C2 (Av=0) and C3 (4050 Å) bands. Interpretation of these profiles with the vectorial model allowed us to trace the variability of the gas production rate vs. time before the observations. It has been shown that the comet increased its gas production rate of a factor 3 on 22.9 March 1986, then it decreased to half the 23.1 March 1986.

**OBSERVATIONS.**

As part of a coordinate project of multiwavelength observations of Halley comet, long slit visible spectroscopic observations have been made, during the post-perihelion, at the European Southern Observatory (Chile) from March 19 to March 23, 1986 when the comet was about 1 and 0.80 A.U. respectively from the sun and from the earth. We used the 1.52 m telescope, equipped with a Boller & Chivens spectrograph and a 3 Stage EMI tube + photographic plates as detector. The image scale was 19.4 arcsec/mm on the slit plane, corresponding to 87 arcsec/mm on the photographic plate. The entrance slit height was 8.09 arcmin on the sky and gave a comet spatial coverage of about 2.8 10^5 km. With a grating of 1200 l/mm (reciprocal dispersion equal to 59 Å/mm) the whole optical range was covered with two exposures (3650-5350 and 5000-6700 Å). With a slit width of 150 micron the FWHM of the instrumental profile was about 4 Å, in the whole spectral range. The exposure time ranged from 1 min to a maximum of 60 min in order to correctly expose both weak outer coma and intense inner coma features. The slit orientation was either parallel and perpendicular to the sun direction. As suggested by the International Halley Watch, also spectra of solar analog stars (Landolt #102-1081 and #106-1146), and flux standard star (HD 117880) where obtained during each observational run.

**SPECTRA REDUCTION.**

All the spectra have been digitized with a PDS microphotometer using a scanning aperture of 100*25 μm² - corresponding to 8.7 arcsec along the slit direction (and equivalent to roughly 5000 km on the comet) and to 1.5 Å in the spectral domain. The spectra have been photometrically calibrated (d => I), corrected for the 'S' distortion (due to the intensifier tube), wavelength calibrated and corrected for the atmospheric extinction. Finally, the spectra have been converted in relative intensity units by using the instrumental spectral response, determined with the spectra of the solar analog stars.

To obtain the gas emission the contribution of the dust emission had to be subtracted. Since the dust spectral trend is obtained by convolving the solar flux spectrum (A'Hearn et al. 1983) with our measured instrumental profile. The spatial profile of the dust emission was measured, along the slit direction, in some spectral regions with no detectable gas emission. By multiplying the spatial and spectral distributions a matrix with the 2-D spectrum of the dust was determined. The 2-D spectrum of the gas component has been finally obtained by subtracting the dust matrix from the total emission matrix. Since the dust contribution was high especially in the inner coma region, the gas emission for species with small scalelength (as e.g. C3) was obtained with a relatively large error.

Wavelength integrations over the considered spectral bands give the spatial distribution of the relative emission of the selected species.
Fig. 2 - Spatial distribution of relative band emission of $C_3$ (4050 Å) on 23.3 March, 1986 along the sun direction. Sun is on the right.

INTERPRETATION OF THE RESULTS.

Profiles of the relative emissions as a function of the distance from the nucleus for CN ($\Delta v=0$), $C_2$ ($\Delta v=0$) and $C_3$ (4050 Å) are obtained using spectra with different exposure time. Figs. 1 and 2 represent typical profiles of a long lifetime (CN) and short lifetime ($C_3$) elements along the solar direction. In the CN profile is clearly visible the asymmetry due to the effect of the solar radiation pressure. As for the pre-perihelion data (Falciani et al., 1986, 1987), the emission profiles along the solar direction have been compared with those obtained in the laboratory under assuming the model of Falciani et al. (1986), in order to interpret them with the vectorial model (Falksnen, 1984). However, the corrected profiles have still a residual asymmetry and an internal scale length, due to the time variation of the gas production rate, well observed phenomena during this Halley comet apparition (Falksnen et al., 1986).

The need to take into account of a time dependent gas production rate $Q(t)$ introduces a too large amount of independent parameters. We thus decided to use the published values for the lifetimes and velocities for both the parent and daughter elements (A'Hearn, 1982, Cochran, 1985). The model free parameter becomes the time dependent gas production rates.

Figs. 4, 5 show a comparison between the observed data on March 23.30, 1986 (crosses) and the vectorial model calculation (full line), for the antisolar profiles of CN ($\Delta v=0$), $C_2$ ($\Delta v=0$) and $C_3$ (4050 Å). The best fit parameters are quoted in Tab. I. It can be seen that the agreement between the measured data and model calculations is fairly good. For all the three species the gas production rate increases of a factor 3 around 0.4 days before the observations, and then it decreases of a factor 2 0.2 days later.

The data analysis is under completion and the next step will be the determination of the temporal (and, possibly the spatial) absolute $Q(t)$ values for the various considered species in order determine the variability of the Halley comet during the considered period.
where: $t_p, t_d$ are the dotted lifetimes for parent and daughter

$v_p, v_d$ "" velocities ""

$Q$ is the molecule production rate normalized to 1 for

the time of observations.

Fig. 5 - Spatial distribution of relative band emission of $C_3$

(4050 Å) (crosses) and vectorial model calculation (full line).

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R., Jackson, W.M., McFadden, L.A., Patriarchi, P.,
Schleicher, D.G., Tozzi, G.P., Wallis, M.K., Weaver, H.A.
(Halley's comet issue).

THE TAIL LENGTH OF COMET HALLEY FROM HISTORICAL DATA

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European Southern Observatory, Garching.

Abstract: About 200 observations from AD66 to 1910 of the tail length of Comet Halley have been used to derive the mean tail length of the comet as visible to the naked eye under very good observing conditions. The curve, covering an interval of \(-45 \leq (t-T) \leq 80\) days, is skewed and peaks at \(-55\) million km for \((t-T) = 18 \pm 8\) days. There is no indication for a secular decrease of the tail length.

I. Introduction

Much discussion has gone into the question whether Comet Halley has betrayed any secular decay during its recorded history. Contrary to previous claims no such decay is revealed by reports on its brightness; unexpected reports on brightness are rather explained by the comet’s irregular activity (and perhaps outbursts as in 1066) as well as by inaccuracies of the chroniclers, than by a systematic trend (Broughton, 1979; Tammann and Véron, 1985). Also the great success of the orbit reconstruction (Yeomans and Kiang, 1981), which is based on Marsden’s et al. (1973) model of nongravitational forces, implies a secularly constant outgassing rate (Yeomans, 1985). In view of the dynamical age of the comet of much more than 16000 years (Yeomans, 1985; cf. also Hughes, 1985) detectable secular changes are indeed not to be expected.

An additional test is here presented for possible secular changes of Comet Halley; it is based on historical data on the observed tail length.

II. The Data

About 200 visual naked-eye estimates of the tail length of Comet Halley have been collected from various sources for the apparitions of AD66 to 1910. The Chinese observations of the tail length were taken from Ho (1962). The relevant observations for Europe were drawn from Pingré (1783, 1784), Holetschek (1896), Vsekhsviatsky (1958), and in a few cases from contemporary sources. For the apparition of 1910 the visual tail observations are compiled in the Memoirs of the British

Fig. 1. The linear tail lengths in astronomical units of Comet Halley from historical records from AD66 to 1910. The abscissa gives days before and after perihelion. The full drawn line is an upper envelope; it is assumed to reflect the mean tail length to the naked eye under very good observing conditions. The closed triangles (*) are the photographic 1910 observations by Curtis (1910). The dashed line is adapted from Yeomans (1981).
The Chinese observations of the angular tail length are given in "chi" or "zhang" units; they are assumed that 1 zhang = 100 miles (Kiang, 1972). This conversion agrees somewhat better with European observations than Clark and Stephenson's (1977) relation 1 chi = 10°. In the latter case there would be a hint that Comet Halley's tail has secularly increased in length which we take as improbable. Some European estimates of the tail length are given in "chi" or "zhang" units; they are augmented by the data of Barnard (1914) and Curtis (1914). The latter observations, but one, were made photographically; they are supposed to reflect very good, but not exceptional observing conditions. The tail curvature becomes important only when the Earth is near to the ascending or descending node of the comet at the time of observation. This situation arose during the observations of April 9-14, 1837, and May 1-5, 1759; they are hence omitted in the following discussion.

III. Results

The linear tail lengths are plotted in Fig. 1. For a given time (t-T), where T is the time of perihelion, the data scatter widely. The reason is obvious: the visible tail length depends sensitively on the observing conditions. The comet's angle from the Sun, moon light, clouds and haze, zodiacal light and atmospheric extinction may reduce arbitrarily the apparent size of the tail. Recorded tail lengths are hence always minimum values. In addition, night-to-night variations of the comet's activity and of the magnetic polarity of the Solar wind may cause strong fluctuations of the intrinsic length of the tail.

For these reasons a mean line through the observed points is difficult to justify. Instead, we have drawn a smooth upper envelope encompassing about 90% of the observations. The significance of this envelope is that it should reflect the mean linear tail length under very good observing conditions.

The data in Fig. 1 agree reasonably well for different apparitions over the intervals of observations. Some points lie above the envelope; they are assumed to be observed under exceptionally favorable conditions. Messier's observation of April 1, 1759, (at t-T = 19 days) may be off by a factor of 2.5 (instead of the recorded 25°). The very long tail (19° corresponding to 0.49 a.u.) reported by de la Nux for May 14, 1759 (t-T = 62 days), remains unexplained.

A particular problem is posed by the 1910-observations by E.E.Barnard (1914). While his observations from May 3-24 agree on average very well with the estimates of other observers, his estimates for May 26 to June 6 surpass all other simultaneous observations by an average factor of 2.7. His maximum tail length of 0.72 a.u. on June 6 (t-T = 47 days), for which date the upper envelope predicts only 0.25 a.u., is unparalleled. The only explanation we can offer for this curious situation is that Barnard had very exceptional observing conditions at Yerkes Observatory around June 1. Because the upper envelope in Fig. 1 is supposed to reflect very good, but not exceptional observing conditions Barnard's estimates are not plotted.

The upper envelope in Fig. 1 is clearly skewed. While the visual tail observations begin at (t-T) = -46 days (in 1378 from Far Eastern sources) they extend to (t-T) = 76 days in 1759 and to even 77 days in 1910. The maximum tail length of ~0.35 a.u. is reached at (t-T) = 18 ± 8 days.

A naked-eye tail length function has been given previously (Yeomans, 1981). It is also shown in Fig. 1. There is no agreement between this curve and the presently adopted curve. There are a number of reasons for this disagreement. The line by Yeomans is defined as the mean curve through the observations; it thus corresponds to 'average' observing conditions, whereas our upper envelope supposedly reflects very good conditions. Yeomans' curve considers only the apparitions of 1759, 1835, and 1910, and for the latter apparition high weight has been given to the observations by Barnard, which we believe to be incomparable for the time after May 25, 1910, for the reasons stated above. We have instead used here an extensive body of observations for 1910. Finally Yeomans has used the long tail observed by de la Nux on May 1, 1759 (t-T = 49 days), when the Earth was near the comet's descending node; as discussed in Section II this observation is excluded here.

IV. Conclusions

From angular tail length estimates of Comet Halley, spanning a millennium, linear tail lengths were derived. A plot of the linear lengths against time before and after perihelion define reasonably well an upper envelope (Fig. 1). This curve is interpreted to give the average tail length as visible to the unaided eye under very good observing conditions.

There is no indication at constant heliocentric distance that Halley's tail has faded during the last two millennia. The upper envelope curve is skewed with respect to the perihelion date. The tail length peaks about 18 days after perihelion when the tail measures ~0.50 a.u. Being a naked-eye object, linear tail lengths were derived. A plot of the linear lengths against time before and after perihelion define reasonably well an upper envelope (Fig. 1). This curve is interpreted to give the average tail length as visible to the unaided eye under very good observing conditions.

A more detailed analysis of the historical data on Comet Halley's tail does not seem to be justified. Even if the observing conditions were the same, the positions of the Sun and the Moon and the altitude of the comet were individually
reconstructed, factors like tail curvature, air transparency, haze, and cloud coverage would remain unaccountable.

Acknowledgement: Financial support of the Swiss National Science Foundation is gratefully acknowledged.

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THE PLASMA TAIL OF COMET BENNETT 1970 II

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A set of fourteen large-scale exposures of comet Bennett 1970 II between 1970 April 27 and 30 is evaluated. The solar wind velocity is determined from the aberration angle of the plasma tail. Its radial component has a minimum value of 70-100 km/s in the comet's environment: 50° off the ecliptic at a distance of 1 AU from the Sun. This value is 3-4 times less than the satellite data recorded at the Earth's orbit. The two plasma kinks, visible on 1970 April 30 in the comet tail, moved from the nucleus at a mean radial velocity of 81 and 76 km/s, respectively. No disconnection event appeared in the plasma tail.

Keywords: Comet Bennett 1970 II, Disconnection event, Plasma tail, Solar wind.

1. INTRODUCTION

Comet Bennett 1970 II counts among a few comets from the last decades, at which a long plasma tail was observed. This period is characterized by intense space exploration, and sometimes called the satellite era. Hence, peculiarities and motions of different phenomena in the comet's plasma tail can be studied in conjunction with the interplanetary magnetic field and solar wind flow data obtained by the satellites.

Plasma tails of comets have been studied for many years. In spite of the available satellite data on the solar wind and interplanetary magnetic field, an adequate theory of the formation and motion of the kinks and rays does not yet exist. Unfortunately, the comets usually move far from the Earth's orbit, where the space probes for measuring the interplanetary magnetic field and solar wind flow mostly operate.

We have used a set of fourteen large-scale exposures of comet Bennett 1970 II (Table 1) for the study of the solar wind at a high ecliptical latitude, and for the determination of the motion of plasma kinks in the tail relative to the nucleus. Short time intervals between the exposures—from 11 to 40 minutes in one night—have enabled us to describe their kinematic behavior and interaction with the interplanetary magnetic field and solar wind flow.

The plates were exposed between 1970 April 27 and 30 with the 30/150 cm astrograph of the Skalnate Pleso Observatory of the Astronomical Institute of the Slovak Academy of Sciences. Their exposure time varied from three to ten minutes.

2. COMET ORBIT GEOMETRY

Comet Bennett moves in a nearly parabolic orbit in a plane almost exactly perpendicular to the ecliptic. The inclination of its orbit is 90.04°. The comet crossed the ecliptic plane at 223.96° of ecliptical longitude. During the investigated time interval the comet had, therefore, an almost constant ecliptical longitude, approximately equal to that of its ascending node. The perihelion of the orbit is 5.85° below the ecliptic, 0.54 AU from the Sun. The comet passed it on 1970 March 20.05.

The relative positions of the comet, the Sun, and the Earth on 1970 April 28/29, 1. e. within the investigated period, are shown in Figure 1. The comet was 49.86° above the ecliptic at nearly the same heliocentric distance as the Earth: 1.00 AU and 1.01 AU, respectively. The distance between the comet and the Earth was 1.32 AU. The phase angle Sun-comet-Earth was 45°, and the Earth preceded the comet by 70 to 40 of ecliptical longitude. Therefore, the viewing direction from the Earth was almost perpendicular to the comet's orbital plane. The plasma tail on the plates is narrow, with rays asymmetrically distributed with respect to the Sun-comet direction.

3. METHOD OF ANALYSIS

For the study of plasma tail phenomena it
is necessary to determine their cometocentric coordinates. For this purpose, the coordinate frame of the exposures was provided by 45 reference stars from the Smithsonian Astrophysical Observatory Star Catalog, with the correction for their proper motions. The quantities for the determination of the solar wind velocity and plasma kink motions—spherical coordinates of the Sun and the comet, ecliptical longitude and cometocentric coordinates of the Earth, the comet’s orbital velocity components and equatorial spherical coordinates, and the tabulated values—were calculated by means of our own computer programs on Hewlett-Packard 9830.

The coordinates of the comet were calculated using the orbital elements as determined by Marsden (1986). The radial direction from the Sun to the comet nucleus was fixed by the great circle crossing the Sun and the comet nucleus (Dobrovol’ski, 1966).

4. SATELLITE DATA

The satellite data on the solar wind velocity and on the interplanetary magnetic field between 1970 April 24 and May 4 are plotted on Figure 2. The data on the solar wind velocity are from the VELA 2-6 and OGO 5 satellites (King, 1977). The former operated at the distance of 16 Earth radii from the Earth’s surface, and latter at 0.04-2.3 radii, respectively. Between 1970 April 27 and 30 the solar wind velocity was found to vary from 320 to 450 km/s. Unfortunately, during this period ion density and temperature were not measured.

The magnetic field parameters are from the Explorer 41 (IMP-5) satellite (King, 1975), which operated at the distance of 0.04-2.3 Earth radii from the Earth’s surface. During the investigated time interval the satellite recorded magnetic field intensities of 2.6 to 5.6 nT.

No discontinuities in the longitude and latitude angles were recorded. This indicates that there were no changes of the polarity.

5. PLASMA TAIL

On the seven exposures between 1970 April 27 and 28 (Table 1), i.e. on the night of April 27/28, the plasma tail was apparently separated into two parts occupying opposite sides of the tail axis. The length of the tail on these plates is 1.74°-2.69°. The differences are probably due to the exposure time, which varied from three to ten minutes. The plasma tail on the exposures of April 27.983, 27.992 and 28.000 extends out of the field of the plates. Therefore, the tail must have been longer than 2.7°. On the pictures it is possible to see the formation of plasma rays asymmetric to the tail axis. They are clearly visible on the side of the tail preceding the apparent motion of the comet. There are moderate but bright kinks and disturbances.

On the three exposures of April 29 (Table 1) the composite structure of the plasma tail is not so clear as on the preceding night. The asymmetric formation of the plasma rays is less expressive, too. A weak plasma cloud is visible on the plates of April 27/28, the plasma tail was apparently separated into two parts occupying opposite sides of the tail axis. These may be due to symmetric plasma rays. There are asymmetric plasma rays, too. One of them becomes gradually deformed within this period, and assumes the form of a tail disturbance. However, this disturbance is not so expressive as on the plates of 1970 March 30 and April 4 investigated by Jockers and Lüst (1973). The length of the plasma tail on the exposures of April 30 is about 2.2°.

6. PLASMA TAIL AND SOLAR WIND

Due to the interaction of the tail’s plasma with the solar wind flow, there are some deviations of the comet’s plasma tail from the radius vector from the Sun. From this aberration angle it is possible to determine the velocity of the solar wind in the comet’s region. This problem is discussed in many papers, e.g. Brandt (1969), Jockers and Lüst (1973), Niedner et al. (1978), Tarashchuk (1974).

The measured aberration angles between the projection of the radius vector Sun-comet and the axes of the comet plasma tail on the exposures are listed in Table 1. The + sign means that the vectors Sun-comet, comet-Earth, and the tail axis form a right-handed vector system.

The velocity components of the solar wind velocity obtained from the aberration angles are listed in the next columns of Table 1. They were calculated using the formulae of Jockers and Lüst (1972). It is essentially impossible to determine the tangential velocity vector from the measurements of the tail aberration angle alone. Therefore, we first assumed that the tangential component of the solar wind is zero.

The last two columns give the minimum value of the tangential component of the solar wind speed under the assumption of the...
Table 1. Solar wind flow velocity between 1970 April 27 and 30

<table>
<thead>
<tr>
<th>No</th>
<th>Date middle of exposition UT</th>
<th>Exposure time</th>
<th>Aberration angle</th>
<th>Solar wind flow velocity minimum radial tangential = 0</th>
<th>Solar wind flow velocity minimum tangential = 90</th>
<th>Solar wind flow velocity minimum radial = 180</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1970 April 27</td>
<td>min</td>
<td>deg</td>
<td>km/s</td>
<td>km/s</td>
<td>km/s</td>
</tr>
<tr>
<td>2</td>
<td>27.932</td>
<td>10</td>
<td>+1.0</td>
<td>92</td>
<td>0.1</td>
<td>12.1</td>
</tr>
<tr>
<td>3</td>
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<td>98</td>
<td>0.1</td>
<td>12.1</td>
</tr>
<tr>
<td>4</td>
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<td>94</td>
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</tr>
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<td>5</td>
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<td>97</td>
<td>0.1</td>
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</tr>
<tr>
<td>6</td>
<td>28.000</td>
<td>9</td>
<td>1.3</td>
<td>91</td>
<td>0.4</td>
<td>11.2</td>
</tr>
<tr>
<td>7</td>
<td>28.010</td>
<td>3</td>
<td>2.9</td>
<td>100</td>
<td>0.0</td>
<td>11.6</td>
</tr>
<tr>
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<td>10</td>
<td>+1.0</td>
<td>84</td>
<td>0.6</td>
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<tr>
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<tr>
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<tr>
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<td>11.8</td>
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</table>

Ecliptical latitude +50°. Distance from the Sun 1 AU. For sign < and > see text.

radial velocity component of 100 km/s and 400 km/s, respectively. It is the minimum value only, because the deviation angle of the solar wind velocity vector from the comet's orbital plane is unknown. The tabulated values of the tangential velocity component are marked by +, if the aberration angle is enlarged by a tangential velocity component of the solar wind, and by - in the opposite case. The first assumed value of the radial velocity component is consistent with the minimum radial velocity determination, the second value with the satellite data for a quiet solar wind flow (Figure 2).

The velocity of the plasma tail ions, carried along by the magnetic field of the solar wind, does not correspond to the solar wind velocity. The velocity of the ions is reduced by the kinetic energy needed for carrying along the dust particles (Parashikov, 1970). The angular deflection of the wind vectors to the comet heliocentric direction will be considered later in the text.

On 1970 April 29-30 and at the computed minimum value of the radial solar wind velocity component varied between 20-100 km/s. On April 27-28 and a little smaller, 40-70 km/s. These values apply to the comet trajectory, which is situated at the same heliocentric distance as the Earth, and approximately at the same ecliptical longitude where the satellites were operating, but 30° off the ecliptic. When compared with the satellite data on the solar wind velocity, 20-450 km/s (Figure 2), our value is 3-4 times smaller than that at zero ecliptical latitude. The disproportion is in fact smaller, because we were only able to estimate the lower limit of the solar wind velocity.

7. MOTIONS AND VELOCITIES OF THE KINKS

On the four exposures of 1970 April 30 (Table 2) it was possible to locate reliably two details. The motion and radial velocities of these plasma kinks were determined from six time intervals, defined by selected exposures. The length of the maximum time interval between exposures was 79 minutes, that of the minimum time interval 12 minutes.

During the maximum time interval, the
first kink receded from the comet nucleus in the radial direction by more than 1.82x10^5 km; from the distance of 1.84x10^5 km from the nucleus (exposure of April 30.903) to the distance of 2.22x10^5 km (exposure of April 30.903). The radial velocity determined from the individual time intervals varies between 79 km/s and 81 km/s (Table 3). The mean radial velocity of the first kink is 80.9 ± 0.9 km/s.

The second kink receded during the maximum time interval from the nucleus by 1.36x10^5 km in the radial direction; from the distance of 2.92x10^5 km from the nucleus (exposure of April 30.903) to the distance of 3.28x10^5 km (exposure of April 30.908). The radial velocity, as determined from the individual time intervals, varies between 60 km/s and 81 km/s (Table 3). The mean radial velocity of this kink is 76.0 ± 1.0 km/s. Its uncertainty is larger, because this kink is not so well defined.

The positions of the kinks were determined in the cometary rectangular coordinates x, y in the comet's orbital plane by the formulae of Konopleva and Rozenbush (1974), from the measured equatorial coordinates on the plates. The individual positions of the kinks in the comet tail relative to the nucleus are plotted on Figure 3. They are removed from the nucleus according to the exposures sequence.

The motion of plasma kinks, as well as the aberration angle of the plasma tail, are due to the interaction of the cometary plasma with the solar wind flow. The higher value of the mean radial velocity of the kinks, 76-81 km/s, than that determined from the aberration angle for the solar wind on April 30, 60-71 km/s, is due to the different methods used. In the first case we determined velocity of the individual plasma kinks. Their positions in the comet tail relative to the nucleus can be determined more precisely than the aberration angle in the second case. Moreover, the solar wind radial velocity determined from the aberration angle is the lower limit only.

8. CONCLUSIONS

Between 1970 April 27 and 30 no disconnection event in the plasma tail of comet Bennett 1970 II occurred. The length of the plasma tail, as recorded on our exposures, was about 6.59.

Between April 27 and 29, the radial component of the solar wind velocity, as determined from the aberration angle of the plasma tail, had a minimum value of 84 km/s to 100 km/s. On April 30 this was a little smaller, 60 km/s to 71 km/s. The minimum value of the tangential component varied between April 27 and 29 from 0.1 km/s to 0.6 km/s, or from 11 km/s to 13 km/s, under the assumption that the radial velocity component was 100 km/s and 400 km/s, respectively. On April 30 the tangential velocity component was between 1 km/s and 2 km/s, or 12 km/s and 14 km/s, respectively.

On the exposures of April 30 the positions of two plasma kinks were determined. They moved from the nucleus at a mean radial velocity of 81 km/s and 76 km/s, respectively.

9. REFERENCES

1. Introduction
As a contribution to the IHV activities among others comet P/Halley has been observed at the 90-cm telescope of the Jena University Observatory. This paper presents the results of the observations together with an analysis of the behaviour of the dust and gas components of P/Halley. For various gaseous species production rates have been derived as well as a relative production rate for solids. The structure of the coma has been investigated by means of photometric sections. Section 2 of the paper gives the results of the photometric observations. In Section 3 the estimates for the production rates and their variation with heliocentric distance are presented. Section 4 is concerned with the results of photometric sections through the cometary coma and makes a comparison with models of dust and gas propagation.

2. Photometric photometry
The observations were carried out using six standard HW filters with central wavelengths between 356 nm and 514 nm. The photometric photometer is computer-controlled, detector is an EMI 6256C type photomultiplier (uncooled). The results for comet P/Halley are published in STECKLUM et al. (1987). The measurements were tied to the magnitudes adopted by PFAU and STECKLUM (1986) for HW standard stars. As recommended by the Discipline Specialists of the HW Photometry and Polarimetry Net the zero points in all filter bands are arbitrarily defined by the V magnitude of the star HD 3379 (V = 5.88 mag). The standard deviations of our comet magnitudes can be estimated to be 0.05 mag in all bands except in the C2 filter where it may be a little bit better. Owing to the continuously rotating filter wheel in the photometer the colour indices are very reliable.

3. Production rates of comet P/Halley
The derivation of the product on rates is based on the emission band fluxes which have been estimated according to the standard procedure (cf., STECKLUM et al., 1987) using the values of A'Hearn (1986) to convert the emission band fluxes which have been estimated according to the standard formula

\[ \lg M(R) = \lg F(R) + 27.4497 + 2 \lg \rho - \lg g, \]

where \( M(R) \) is the number of molecules within a cylinder of radius \( R \) defined by the photometer diaphragm and extending entirely through the coma, \( F \) is the emission band flux in cgs units; \( \rho \) and \( g \) are the heliocentric and geocentric distances of the comet, respectively, in AU; and \( g \) is the fluorescence efficiency (cgs units) per molecule at 1 AU. Values of \( \lg g \) of -12.057 for \( C_3 \) and -12.00 for \( C_2 \) have been used in accordance with MILLIS et al. (1993). Due to the Swings effect the fluorescence efficiency of \( CN \) varies with the comet's heliocentric radial velocity. The appropriate values were taken from TATUM and GILLESPIE (1977). Column densities for CO have not been estimated since we could detect CO emission with sufficient accuracy only at two occasions (December 5 and December 22). The results for the column densities for \( C_2 \), \( C_3 \), and \( CN \) are listed in columns 7-9 of Table 1.

The derivation of the production rates without applying a model of the comet's intensity distribution requires a variable diaphragm size to observe a fixed area at the comet's surface. However, this was not the case with our observations. Therefore, we applied the Hase model (HASE, 1957), to convert the observed column densities to production rates. The scale lengths used for the computation of the production rates are from A'Hearn et al. (1981). The production rates for the gaseous components are given in columns 10-12 of Table 1. A relative production rate of the solid component has been estimated from the continuum flux using the assumption that the dust scatters isotropically and that the dust outflow is spherical symmetric. In this case the column density of cometary dust is proportional to the size of the coma covered by the dia-

PRODUCTION RATES OF GASES AND SOLIDS IN COMET P/HALLEY DURING THE 1986 APPARITION

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From photoelectric photometry at our 90-cm telescope we derived continuum and emission band fluxes within the bandspasses of the standard IHV filters. These data were converted to give production rates for \( CN \), \( C_3 \), \( C_2 \), and solids. The observations cover the range of pre-perihelion distances from 2.1 AU to 1.1 AU and include one post-perihelion measurement at 1.7 AU. The production rates of the gas components show a strong dependence on heliocentric distance. The result is compared with the behaviour of other comets and theoretical considerations. The dependence is less steep for the solids. This may be due to relatively pronounced backscattering of the grains.

During one pre-perihelion night (\( r = 1.5 \) AU) intensity profiles along three sections through the coma of P/Halley were measured. Compared with the Hase model the profiles show a global anisotropy of the coma and possibly local structure.
The very strong dependence of the production rates on heliocentric distance is not unusual among comets, and it has been observed, e.g., for comets P/Stephan-Oterma, P/Encke and others. It is understandable as the result of a positive feedback mechanism proposed by HILLMICH (1981) and KIEFFER (1981) which results from the much larger cross section of the dust halo compared to that of a pure nucleus, and the effects of multiple scattering, and thermal radiation. However, differences in the geometry of various cometary nuclei may influence the strength of the phenomenon. The difference between the dependence of the gaseous components and the weaker ones may be explained by scattering effects. Our first observation of the scattered light at scattering angles near 180° and may be influenced by enhanced backscattering. Evidence for enhanced backscattering in comets was given by KIEFFER et al. (1980), HILLMICH et al. (1981) and KIEFFER (1981), and by GIESE et al. (1980) for cometary candidate particles. A match to the derived exponents of the gas production rates requires a decrease of the scattering function by a factor of about four in the argument range from 180° to 170°. This leads to the suggestion that comet P/Halley shows a more pronounced backscattering than other comets. However, from the results of the IR photometry of DUCHET et al. (1987) one can draw the conclusion that the dependence of the dust production rate on heliocentric distance was not very different from those of gaseous species. CATALANO et al. (1986) derived from their IHW-narrowband photometry a nearly constant dust production rate within the same heliocentric distance interval which is in disagreement with the former mentioned findings. The exponents of dependence of the gas production rates of CATALANO et al. (1986) are smaller than the values presented here.
Fig. 1. Relative production rate of solids in comet P/Halley as a function of heliocentric distance. The full circle refers to the post-perihelion observation.

Fig. 2. Production rate of $C_2$ as a function of heliocentric distance. Note the outstanding value at $\lg r = 0.274$ which might indicate enhanced cometary activity.

Fig. 3. Production rate of $C_3$.

4. Density profiles of comet P/Halley

During the observation at 1985, December 22/23 the brightness profile of the coma was measured along three sections, each starting from the comet's center. The first one was carried out in the direction of motion (sunward), and the third in the antisolar direction. The position angle of the velocity vector of the comet was 240° and the position angle of the second section 112°. The geometry is shown in the insert of Fig. 5. The stepsize of consecutive measurements was 21'5 at a diaphragm radius of 14'25. The derived emission band and continuum fluxes have been normalized to the maximum values at the coma center. To compare these results with simple models of dust and gas outflow the diaphragm integration has to be taken into account. This has been done using the simple model of dust outflow and the Hase model for the gaseous species. The results of the observations in comparison with the models are shown in Figures 5 and 6. For the computation of the theoretical profiles the scale lengths of A'HEARN et al. (1981) have been used with the exception of the $C_2$ parent scale length which did not fit the data well. A good match was obtained using the CN parent scale length of NEWBURN and SPITZER (1984).

All theoretical profiles qualitatively agree with the measured profiles. However, there are systematic deviations in the sense that with the exception of the profile for the solids, the measured values for the sunward section are smaller than the theoretical ones, whereas the data for the tailward section are larger than the theoretical ones. The second section shows an intermediate behaviour. This reflects a global anisotropy of the coma which is expected due to the interaction with the solar wind and radiation. This anisotropy is even present in the data for the solids. However, the
Fig. 4. Density profiles of the density of solids along three sections through the coma. The diagonal lines are in the direction of the open circle. The vertical bars give the part of the coma covered by the diaphragm. The dashed line is the theoretical profile.

Theoretical profile for this component lies over the measured values which may be a consequence of imperfect background correction.

The results confirm the statement that the laser model for the various species together with the simple model of dust outflow give a good overall description of the coma's intensity distribution, i.e., therefore, suited for the derivation of production rates from narrowband photometry without introducing large systematic errors. However, a better agreement between observed and theoretical profiles can only be reached by applying more elaborated models, e.g., of FESTOU (1981a, b).

We are grateful to Dr. A'Hearn, University of Maryland, who put the Standard Comet Filters at our disposal and to Dr. REHNUM for his help with the observations.

References:
The outbursts of cometary brightness have been attracting the astronomers attention for more than a hundred of years. They play a significant role in the study of physical nature and evolution of comets. An outstanding Soviet astronomer S.K. Vsekhsvyatsky (1) pointed out the corpuscular fluxes as a plausible factor being responsible for the variation of cometary brightness. He was the first to suggest that the outbursts are generated by solar corpuscular fluxes. The comet as well. According to O.V. Dobrovolsky (2) the interaction between protons of solar origin and the comet should be displayed variability. This fact indicates that besides corpuscular fluxes (Halley, Schwassmann-Wachmann, Finsler) and give 100% correlation, and some of them are not affected by solar activity. This fact indicates that besides corpuscular external effect it is necessary, for generating the outbursts, the existence at present moment of corresponding conditions in the comet as well. According to O.V. Dobrovolsky (2) the interaction between protons of solar origin and the comet should be displayed by cometary outbursts with characteristic variations of the appearance of the head.

At investigating the relation between outbursts and solar activity, and revealed the existence of direct correlation for the majority of comets. It has been stated that some comets are very sensitive to corpuscular fluxes (Halley, Schwassmann-Wachmann, Finsler) and give 100% correlation, and some of them are not affected by solar activity. This fact indicates that besides corpuscular external effect it is necessary, for generating the outbursts, the existence at present moment of corresponding conditions in the comet as well. According to O.V. Dobrovolsky (2) the interaction between protons of solar origin and the comet should be displayed by cometary outbursts with characteristic variations of the appearance of the head.

To interpret the observed data indicating the effect of solar wind on comets a mathematical model of an outburst has been developed based on the knowledge of cometary nucleus as a conglomerate of various ices and refractory impurities (5). Surface layer of such nucleus, due to thermobarodestruction (from the experiments carried out by L.A.Kajmakov et al. (6-8)) should be destructed periodically. As a result, icy grains come into the cometary coma and form a halo at its periphery. In the solar radiation field the halo of icy grains of a centimeter size may exist for a sufficiently long period. In case the comet gets into corpuscular flux during this period the icy grains with structural imperfections, including cracks, would be destructed by energy particles of solar wind. The enhancement of solar light reflection area due to fragmentation would result in the increased cometary head brightness.

For a quantitative estimation of time dependence of icy grain halo brightness after their destruction onset a system of integro-differential equations was set up:

\[
M(t) = \frac{4}{3} \pi \rho N(t) \int_0^{\max} r^2 f(r, t) \, dr
\]

\[
S(t) = 4\pi N(t) \int_0^{\max} r^2 f(r, t) \, dr
\]

\[
\frac{dM}{dt} = -\mu S(t)
\]

\[
\frac{dS}{dt} = 8\pi \frac{\mu - n}{\rho} N(t) \int_0^{\max} r f(r, t) \, dr
\]

where \(M(t), S(t)\) is mass and area of icy grain halo, respectively, \(N(t)\) the number of icy grains in a halo, \(f(r, t)\) size distribution function of icy grains, \(\rho\) the density of icy grains, \(\mu\) and \(n\) are sublimation and fragmentation coefficients representing, respectively, the material mass sublimating or breaking away for a unit time from a unit area.

The system solution at some assumptions led to the result that variation of icy grain halo brightness is of an outburst nature. It has been shown that with due account of contribution of gas-dust atmosphere the estimated photometric light variation curves are in a good agreement - by shape, amplitude and duration - with the observed brightness outburst curves. This model accounts for the dependence of cometary outbursts amplitude and duration on their heliocentric distance and the level of solar corpuscular activity. The result of solution is given in Fig. 1. As is seen, in the process of icy grain fragmentation the halo brightness variation has an outburst behaviour.
Apart from icy grain halo brightness a visible cometary brightness includes the brightness of gas-dust atmosphere as well. Let us discuss in which manner the visible cometary brightness would be affected by the existence of icy grain halo in cometary atmosphere and the variation of its area due to fragmentation and sublimation. Let \( m_3 \) denotes reduced to \( \Delta = 1 \) AU visible brightness caused by solar radiation reflection of icy grain halo, and \( m_2 \) the dust-gas atmosphere brightness, \( m_1 \) and \( m_0 \) the reduced halo brightness of icy grains and cometary head at \( r = 1 \) AU, respectively.

Let us introduce \( \Delta m_1 = m_1 - m_0 \) and \( \Delta m_2 = m_2 - m_0 \) and choose, as a zero level, cometary head brightness at \( r = 1 \) AU. The variation of \( \Delta m_1 \) and \( \Delta m_2 \) values versus heliocentric distance for different relations of \( m_1 \) and \( m_2 \) is given in Fig. 2. The analysis of the picture allows to conclude that the icy grain halo variation due to grains fragmentation (Fig. 1) in all the cases except when

\[
m_0 (r) \Delta m_1 = m_0 (r) + \Delta m_{\text{max}} (r_{\text{bc}}, d)
\]

or

\[
m_0 (r) \Delta m_2 = m_0 (r) + \Delta m_{\text{max}} (r_{\text{bc}}, d)
\]

results in the outburst of cometary brightness. Here \( r_{\text{bc}} \) is the most probable initial size of icy grains, \( n \) the photometric comet parameter, \( d \) : 2/4 \( r_{\text{c}} \), \( T \) the outburst duration.

The outburst amplitude will depend on \( m_1 \), \( m_2 \), \( n \), \( r \) and \( \Delta m_{\text{max}} (r_{\text{bc}}, d) \) values. Provided the condition (27) is satisfied the amplitude increases with \( r_{\text{bc}} \). The amplitude growth rate depends on relation of \( m_1 \) to \( m_2 \) and the outburst duration depends on \( m_1 \), \( m_2 \), \( n \), \( r \) and \( T(r_{\text{bc}}, d, r) \) values. In case \( m_1 > m_2 \) the outburst duration will be longer than the time corresponding to given \( r_{\text{bc}}, d, T \) which is necessary for the icy grain halo brightness to reach the value \( m_0 \); the outburst duration being increased at the expense of increased time of brightness decreasing as the total cometary brightness decreases up to the value \( m_0 \). This results in the increased \( T_{\text{bc}} / T \) relation as compared to that obtained from Fig. 1.

The results of the model proposed are in good agreement with characteristic parameters of cometary brightness outbursts. The model is capable of accounting for the observed outburst amplitudes duration and their variation at different heliocentric distances as well. At large solar distances - both from the model data and observational results - the outburst amplitudes and durations are larger than corresponding values at shorter distances. At short distances cometary head brightness may prevail the icy grain halo brightness, with the result that cometary brightness outburst would not occur.

Within the scope of this model some observed processes in the cometary heads and tails may be accounted for. These are an increased temperature in the inner coma, the existence of short-lived molecules at the head and tail periphery, an intense sweeping out of dust in cometary head, radiation polarization, IR-radiation and other spectral peculiarities, and also the existence of well-developed plasma structures in heads and tails of comets with outbursts.

\[
\text{REFERENCES}
\]

2. Dobrovolsky, D. V.: 1961, Nestatsionarnye protsess sy v kometakh i solnechnaya aktiv-
Catastrophic or nearly-catastrophic collisions are the most important physical process affecting the evolution of asteroids following the primordial phases. After a general review of the current ideas about collisional evolution, also in the light of laboratory impact experiments, the problems concerning the interpretation of asteroid families as outcomes of catastrophic processes are discussed. Finally, it is shown how the present, non completely satisfactory, knowledge of collisional processes can give important indications on the early phases of evolution of the asteroid belt.

1. Introduction

On the basis of the most recent dynamical and physical studies, a tentative and preliminary general scenario of the formation and evolution of the asteroidal belt can be suggested. The evolutionary history of the main belt population can be roughly divided in three phases: (i) an accretion phase ($\sim 10^6$ yr) leading to the formation of planetesimals up to the accumulation of a few "small" planets as Ceres and Vesta; (ii) a phase ($\sim 10^6 - 10^7$ yr) of strong mass depletion in the belt, due to external causes. Probably in the same time an increase of the relative velocities of the asteroidal bodies took place, stopping the accretion processes and avoiding the formation of a planet between the orbits of Mars and Jupiter; (iii) a phase (still active in the present regime) in which disruptive processes caused by high-velocity ($\sim 5$ km/s) collisions generated the present asteroid population composed by a variety of different outcomes of catastrophic or barely catastrophic events.

Even if no direct information on the sequence of primordial events can be achieved with the observations, a careful investigation of the characteristics of the present belt has shown how the understanding of the collisional phase could be fruitful not only for the study of its final outcomes, but even to obtain hints and constraints on the very early stages of the Solar System and on the involved physical processes. The present situation will be reviewed in details, showing how statistical and theoretical analyses based both on the observational data of physical and rotational properties and on impact laboratory experiments, allow to understand the various outcomes of break-up events among the asteroid population (rocky fragments, "pile-of-rubble" structures, binary systems, families, etc.). A special attention will be given to the problem of asteroid dynamical families, which represent a time-honoured but until now puzzling subject. Even if with the uncertainties still present both on their identification and on a reliable three-dimensional description, the statistical analysis of families can already play a key role to solve or to clarify many relevant problems concerning the evolution of the whole asteroidal belt. Finally, it will be shown how some results of these studies can be used to estimate the mass present in the belt at the end of the primordial phases; a fundamental input to understand the physical processes which were active in the very early Solar System.

2. Collisional Evolution

In their seminal paper, McAdoo and Burns (1973) tried to investigate the collisional evolution of the asteroids, predicted by several dynamical models (Weidenschilling, 1980), originated from a large angular momentum transfer during a catastrophic collision. Starting from these observational evidences and theoretical predictions, Farinella et al. (1982) presented a physical interpretation to be applied to the whole population of asteroids, allowing to achieve a semi-quantitative understanding of the observed differences within a common general scheme. They derived the probability of impacts with a given projectile-to-target mass ratio for asteroids of different sizes, taking into account different mass distributions of the asteroid population at the beginning of the collisional process. Then, using the results of laboratory break-up experiments, they showed that most asteroids were fractured by impacts, at least once during their history, as far as one takes into account only the solid state cohesion. However, they pointed out that the influence of self-gravitation and of processes of angular momentum transfer during catastrophic collisions is strongly dependent on the target’s size, resulting in a variety of possible outcomes, mainly in the intermediate size range ($100 - 300$ km).
Comparing the theoretical scenario with the available observational data on asteroid rotations and shapes, they confirmed that the proposed interpretation can lead to a unified understanding of different and apparently uncorrelated phenomena. The analyses performed by Farinella et al. (1982) allowed to state some general conclusions about the role of catastrophic collisions in determining the evolution of asteroids and their present rotational properties. The largest asteroids (D > 300 km) appear not to have been strongly affected by catastrophic events. Their rotational properties confirm that the largest projectile which impacted was not massive enough to overcome their gravitational binding, nor to transfer the amount of angular momentum needed for the formation of binaries or of triaxial equilibrium figures. For what concerns intermediate-size objects, the largest probable impacts were close to the limits for disruption and for the transfer of a quasi-critical amount of angular momentum. In this class one can expect formation of binaries, triaxial equilibrium ellipsoids, and dynamical families. In fact, in this case, self-gravitation prevents the complete disruption of the target: most of the mass is reaccumulated by the mutual gravitational attraction of the fragments. The resulting object can be described as a "pile-of-rubble" or a megaregolith asteroid (Davis et al., 1979; Fujiwara and Tsukamoto, 1980). Such bodies, because of their state of fragmentation, will relax approximately to the equilibrium shapes consistent with their spin rates and therefore will have only minor surface irregularities sustained by the material's strength. It is also worthwhile to notice that if the initial velocity distribution of the fragments has a tail exceeding the escape velocity of the target, few fragments may be able to escape, reaching a heliocentric orbit having orbital elements very close to those of the most massive remnants: an "asymmetric dynamical family" formed by a large primary object accompanied by a small tail of few minor asteroids is then formed.

Going towards smaller targets, the probability of obtaining dynamical families increases significantly. Since a substantial fraction of fragments is not recaptured, in this size range families are no more formed only by the asymmetric tail of high-velocity fragments escaping close to the impact point, but they are originated from bodies ejected in all the directions. We have then the so-called "dispersed families". The usability of the collisional hypothesis for the origin of the most numerous dynamical families was confirmed by Fujiwara (1982), who analysed in details the energy partition during the collisional formation of the Eos, Themis, and Koronis families. The problems concerning the asteroid families will be discussed in more details and experimental data, even if important problems remain open.

3. Break-up Processes: Asteroids and Laboratory Experiments

Even if the most immediate confirmation of the collisional scenario can be found in the observed size-spin-amplitude correlations, the comparison of statistical properties of asteroids with those of the fragments obtained in laboratory catastrophic impact experiments is of decisive importance. This approach, however, exhibits two important drawbacks: firstly, the experiments should cover a wide range of "initial conditions" (mass, shape, rotation, composition, relative velocities of the colliding bodies, and impact geometry), and we are only at the beginning of the phase in which a statistical analysis of the experimental results can be useful to find relevant correlations and to propose interpretative schemes; secondly, there is a difference of 15 to 20 orders of magnitude in mass and impact energy between laboratory collisions and those which take place in the asteroidal belt: the possible differences caused by so widely disparate size scales are still an open and puzzling problem (Holsapple and House, 1986). Both difficulties entail severe limitations to the possibility of an effective comparison. Nevertheless, the available data on mass, velocity, shape, and rotation distributions of laboratory fragments (Fujiwara et al., 1977; Fujiwara and Tsukamoto, 1980; Fujiwara and Tsukamoto, 1981; Capaccioni et al., 1986; Fujiwara, 1986; etc.) can be analysed and a comparison can be attempted with the corresponding quantities pertaining to the asteroids, while for mass and velocity distributions the only direct comparison is with the outcomes of an individual break-up process (i.e., a family: see Sect. 4), rotations and shapes can be compared with those of the whole sample of asteroids.

For what concerns the rotation rate, the very few largest asteroids have presumably retained their original angular momentum through their whole history, while objects larger than about 100 km appear to have been modified in their rotational properties, owing to: (i) catastrophic or barely-catastrophic events, in which, however, the self-gravitation played an important role producing sometimes peculiar equilibrium figures; (ii) loss of angular momentum during large cratering impacts (Dobrovolskis and Burns, 1984). On the other hand, asteroids smaller than 100 km are probably multi-generation fragments produced by catastrophic break-ups: consequently the most fruitful comparison is between them and the laboratory fragments. Even if with a not complete and biased asteroidal sample, it turns out that - on the average - the smallest observed asteroids tend to rotate faster, as resulting from the analysis by Dermott et al. (1984) and also from the most recent data collected by IAU Comm. 15 (see Fig. 13 in Paolicchi et al., 1987). From an analysis of the rotation of laboratory fragments the same trend results, with an approximate relationship (revolution vs R² size), supported also by simple theoretical considerations (Fujiwara and Tsukamoto, 1981).

For what concerns shapes, Catullo et al. (1984) tried to compare statistically the shapes of small asteroids with those of the laboratory fragments. They
took into account the fact that lightcurve amplitudes are only a rough indicator of the real shape of the objects, and therefore reduced the amplitude of laboratory fragments to an aspect angle of 60°, which would be the average value observed during one opposition, if it is assumed that rotational axes are distributed isotropically on the celestial sphere. In conclusion, they found that the distribution of the laboratory fragments and of the asteroids smaller than 100 km are very similar indeed, strongly supporting the idea that small asteroids are fragments generated in impact events resembling (except for scale) those performed in the laboratory. On the other hand, asteroids larger than about 200 km show a complete different distribution characterized in general by a rather low amplitude much like that we might expect for bodies whose shape roughly fits the spheroidal figures of gravitational equilibrium. Only a limited group (about 15% of the sample) presents significantly higher amplitudes, representing probably cases of asteroids relaxed to triaxial equilibrium figures or transformed into nearly-contact binary systems. These results are consistent with those concerning spins; more generally, the qualitative fit between the rotation and shape properties of laboratory fragments and small asteroids strongly supports the collisional scenario. On the other hand, it follows that a deeper understanding of the catastrophic disruption processes is a fundamental tool for further and decisive investigations on the evolution of the asteroidal belt. However, due to the complexity of the physics, the theoretical understanding and the ability to predict the final outcomes (i.e., size, shape, velocity, and rotation distributions for the fragments), given the "initial conditions" of the impact, is still very poor and mostly qualitative.

Very recently, Paolicchi et al. (1987) have tried to obtain at least some of the relevant information by simple semi-empirical approach. Starting from the experimental evidence that the fragments are ejected with an explosion-like velocity field, whose geometry is almost fixed and can be modelled by a few parameters, they have introduced a simple and plausible rupture criterion expressed in terms of the derivatives of this field with respect to the position into the target. Then, they have derived also the average physical properties of the fragments formed in different zones of the target, and have analysed the correlations among these properties for a number of different choices of free parameters of the model. In such a way, they succeeded in performing qualitative and quantitative comparisons with the evidences coming from laboratory data as well as from asteroid properties. Several correlations found in the observations and in the experiments (increasing rotation rates for decreasing sizes, larger velocities for smaller objects, an almost constant ratio between translational and rotational energies, etc.) were confirmed.

This kind of approach leads to interesting comparisons when kinematical relationships are investigated, so that the introduced velocity field approximation appears to be quite adequate. On the other hand, the reliability of the results is poorer when mass distribution and shapes of the fragments are considered. Even from elementary considerations it results that every "local" fragmentation model leads to some very approximate results; for instance, the geometry of fractures analysed in the experiments (Fujiwara and Asada, 1983; Capaccioni et al., 1986) cannot be obviously taken into account by such a simple local model. A lot of future experimental and theoretical work will be an unavoidable prerequisite for a real understanding of the fragmentation processes.

4. Asteroid Families

After the historical papers by Hirayama (1918, 1923, 1928, 1933) the dynamical asteroid families, i.e. clusters in the space of orbital elements, were studied by many authors and from many points of view.

The transition from the visual identification of some anomalous clusterings in the a-e-i space to a kind of analysis allowing quantitative estimates and physical interpretations is not straightforward and requires the solution of a few complex problems.

The first classification of families was based on the osculating elements. However, these parameters (mainly eccentricity and inclination) are strongly affected by planetary perturbations and vary sensibly on time scales much smaller than any reasonable age estimates for the families. The linear secular perturbation theory allows to define more significant and constant elements ("proper elements"), whose clustering is then much more meaningful, as already suggested by the latest Hirayama papers. Nevertheless, the definition of the proper elements themselves is not simple at all. In fact, even using high-order theories, different and often divergent computations were obtained (Williams 1969; Kozai, 1979, 1983), leading to controversial results. Adding these uncertainties to the ambiguities arising from various possible definitions of a "statistically meaningful clustering" it is not a surprise that the various lists of families reported in the literature (Brouwer, 1951; Arnold, 1969; Lindblad and Southworth, 1971; Carusi and Massaro, 1977; Williams, 1979; Kozai, 1979, 1983) strongly disagree each other (Carusi and Valsecchi, 1982). As a conclusion, the only unquestionably real families are the three largest ones (Themis, Eos, and Koronis), already evidenced by Hirayama. For what concerns the recent efforts for a better and more meaningful definition and computation of proper elements, a promising approach can be based on the comparison between analytic computations and numerical integrations (Carpino et al., 1986; Knezevic et al., 1987). In principle, this approach could allow to evaluate really "stable" proper elements, decisive for coming back to the primordial formation processes.

From a physical point of view, the paper by Gradie et al. (1979) summarized the studies performed till 1979, with a particular attention to the distribution of taxonomic types within the Williams' families. They concluded that no naive correlation of the type "same family - same taxonomic type" was detectable, apart from the largest ones, which showed unusual and homogeneous compositions. Similar results have been derived by Zellner et al. (1985) on the basis of an eight-color survey of about 600 asteroids. On the other hand, the numerous small families defined by Williams did not show any correlation of this kind. This result could support the pessimistic conclusion that only the very few largest families are real, but probably the matter deserves a further scrutiny, and perhaps a new interpretation.

The analysis of mass distributions of family members is another major topic, mainly because it allows a direct comparison with laboratory experiments. In the paper by Zappalà et al. (1984) the data were analysed in
terms of the discrete mass distribution defined by Kresak (1977). The results suggest a power law distribution for small fragments, with a general agreement with the corresponding behaviour of laboratory outcomes (see also Capaccioni et al., 1986). However, for some families there is an evident discrepancy with the experiments, concerning the largest remnant, which results too large when compared with the laboratory outcomes. The interpretation in terms of gravitational reaccumulation of fragments onto the largest remnant is straightforward, being also supported by the increase of the ratio $M_{\text{remnant}}/M$ (mass of the largest remnant / mass of the parent body) with the absolute size. The agreement between mass distributions of real families and laboratory experiments can be considered an important support to the collisional theories for the origin of families.

A more difficult and controversial goal of physical studies of families is the reconstruction of the dynamics of the formation process, i.e., the computation of the original ejection velocities of fragments with respect to the parent body. This could allow a new and fruitful comparison between asteroids and experiments. The problem was analysed by Brouwer (1951) and then, adopting Williams' families, by Zappalà et al. (1984). After having fixed the origin in the space of proper elements (center of mass or the largest remnant of a family) it is easy to define the "position" of each fragment $(\Delta a, \Delta e, \Delta i)$. Then it is possible to calculate the velocity components $v_x, v_y,$ and $v_z$ along the directions $S$ (to the Sun), $W$ (normal to the orbital plane), and $T = W \times S$, by means of the classical Gauss perturbation equations to zero order in eccentricity and for an impulsive velocity change:

$$v_x = n a (\Delta e / \sin \tau - \Delta a / a \tan \tau)$$
$$v_y = n a \Delta a / 2a$$
$$v_z = n a (\Delta i / \cos \psi)$$

The angles $\tau$ and $\psi$ are functions of the asteroid true anomaly and orbit orientation at the very break-up moment, and therefore they cannot be known; it follows that the velocities $v_x$ and $v_y$ can be computed assuming various values of these angles. Even if it is not possible to derive the real ejection velocities for each family, statistically one should expect-on the average-an isotropic distribution of the three components. Surprisingly, the velocity distribution results to be far from the isotropy (even with the most favourable assumption on the unknown angles $\tau$ and $\psi$) since r.m.s. values of $v_x$ and $v_y$ exceed by a factor four or five that of $v_z$. This trend is confirmed also by three well established families (Themis, Eos, and Phaethon). Since no physical explanation of this result appears to be plausible, at least within the collisional theory, one should ascribe it to the above mentioned uncertainties in the computation of proper elements $e$ and $i$. While stressing the need of future works in such a direction, this difficulty leads to take into account only the velocity component $v_z$, which depends only on $a$, the most stable element. Zappalà et al. (1984) assumed as real velocity $v_{\infty} = (3)^{\frac{1}{2}} v_e$, where $(3)^{\frac{1}{2}}$ was inserted to account for the other two neglected components, under the assumption of an overall isotropy. The ejection velocity was then computed by correcting for the gravitational slowing-down of fragments escaping from the parent body:

$$v = (v_{\infty}^2 + v_e^2)^{\frac{1}{2}}$$

($v_{\infty}$ is the escape velocity of the largest remnant, a reasonable estimate for the effective mean velocity required to leave the parent body (Farinella et al., 1987)). The mean ejection velocities were found to be of the order of 100 m/s. While this is a reasonable value for large bodies, for which escape velocity is of the same order, it is surprising that even for the smallest families mean ejection velocities lower than 60 m/s are not allowed. Since this cannot be due directly to self-gravitation effects, it seems to indicate a striking discrepancy between asteroidal and laboratory break-up processes, where fragment velocities are in general lower for the same degree of fragmentation. This fact is supported by similar results obtained for the Saturn satellite Hyperion, also interpreted as being the largest remnant of a catastrophic process (Farinella et al., 1983).

More recently, Davis et al. (1985), after a more detailed comparison between families and outcomes of laboratory experiments, suggested as a possible solution of the quoted discrepancies the increase of impact strength due to hydrostatic self-compression. However, this problem is still open, especially for what concerns small bodies and small families.

Finally, one should remark that the distribution of $\Delta a$ within a family can provide some insights on the symmetry properties of the ejection velocity field (see also Sect. 2). After the pioneering investigation by Ip (1979), Zappalà et al. (1984) introduced a quantitative symmetry parameter

$$c = \frac{<v^2>}{<\Delta v>^2}$$

where the mean velocities are computed with respect to the largest remnant. It turns out that the most asymmetric families correspond-on the average—to higher velocities and to larger sizes, in a good agreement with the prediction of the collisional scenario and of the related considerations on the gravitational reaccumulation.

5. Missing Mass in the Belt

Even if a detailed and quantitative scheme of the fragmentation processes occurred during the collisional evolution of the asteroid belt is not yet completely available, it is worthwhile to notice that the preliminary scenario outlined in the previous Sections can lead to some basic information about the original population of the asteroids and the early phases of the Solar System evolution. The overall mass distribution in the protoplanetary circumsolar nebula implies (if we assume a generally regular behaviour) that the amount of small material, within the region presently populated by the asteroids, should have been, at the origin, not less than one Earth mass (Weidenschilling, 1977): a value that exceeds by about three orders of magnitude the present total mass of the asteroids (Kresak, 1977). In order to explain the removal of the missing mass, one can suggest either that it was gradually comminuted by dust or by the disruptive process caused by repeated collisions at speeds of about 5 km/s and then displaced by non-gravitational forces, or that the mass was expelled primordially in the course of the same process that stirred up asteroid orbits and increased the relative velocities at impacts. For discriminating between these possibilities, it is decisive to estimate at least the order of magnitude of the mass present in the belt at the time the accretion was stopped and...
of the relative velocities increased. A recent study by Davi et al. (1985), considering as constraints the properties of Vesta's basaltic crust and of the Hirayama dynamical families, with the new assumptions on the scaling of impact strength above discussed, concluded that the initial population of asteroids was not larger than several times the present belt mass. The previous conclusion supports the hypothesis that most of the mass had to be depleted before the onset of the present collisional regime. A similar result was reached by Farinella et al. (1985) by analyzing the influence of collisions on the asteroid rotational properties as derived mainly by photoelectric photometry of asteroid lightcurves. As already mentioned, Farinella et al. (1986) have shown that in the range 200-300 km an unusually large fraction of objects is observed with rapid spins and large lightcurve amplitudes (i.e., very elongated shapes). They interpreted them as collisionally-formed "piles-of-rubble", held together by self-gravitation and having received a large amount of angular momentum during the impact.

If one misuses the angular momentum of rotation in units (GMR), according to the predictions of the classical theory (Chandrasekhar, 1969), the stable equilibrium figures are represented by triaxial shapes for values of the angular momentum in the range 0.3 to 0.39. Beyond the latter value, binary fission is expected. Actually, in the range 200-300 km we have about 1/3 of the asteroids exceeding the critical value 0.3, assuming that the density does not exceed 3 g/cm^3. Taking into account that both for the terrestrial planets and the largest asteroid (Ceres) the angular momentum is less than 0.1, there is no reason to believe that the elongated triaxial bodies had at the end of the accretion phase a value larger than 0.1 and thus one can reliably assume, as an observational constraint of the collisional evolution process, the fact that about 1/3 of the asteroids of quite large size received by the collisions themselves an amount of angular momentum of the order of 0.3. Assuming a power-law differential mass distribution for the bodies colliding a given target, it is not difficult to derive that the mass of the largest projectile which collided with a 250-km target corresponds to a diameter of about 65 km (namely, a projectile able to produce a "rubble-pile" asteroid). Presently, there are about 450 asteroids larger than 65 km and, consequently, every asteroids of about 250 km had a probability of 15% of colliding with one of them during 4.5·10^7 yr. In conclusion, for having the actual percentage of high-angular momentum bodies, we need that the "initial" population (at the end of the accretion phase) was about 5 times more abundant than the present one; this result is fully consistent with that of Davi et al. (1985). Consequently, the present estimate of the belt mass at the beginning of the "3rd evolutionary phase" (see Sect. 1) can be considered quite reliable. The knowledge of this datum is extremely valuable for the understanding of the earlier phases.

REFERENCES

DISCUSSION

Harris: Dermott has pointed out that the "IRAS dust bands" account for $\approx 10\%$ of the total surface area of zodiacal dust. Likewise, the Eos, Themis, and Koronis families constitute $\approx 10\%$ of the total surface area of all asteroids in the main belt. Therefore it appears possible that most of the zodiacal dust is asteroidal in origin.

Lindblad: We know that meteorite bodies are expelled from the asteroid belt. Is it possible that some of the missing mass in the asteroid population is explained by these meteorites?

Zappala: I think that the meteorite bodies are a product of the collisional evolution of asteroids. Therefore, they do contain a not negligible mass, however this cannot account for a mass depletion three orders of magnitude larger than the present one.

Babadzhanov: Is there any special distribution of the products of fragmentation of asteroids according to their sizes and distances from the main asteroid belt?

Zappala: For what concerns observable bodies, there is a mixing between the original mass distribution and the collisional distributions. I agree that more information can be obtained from the mass distribution of the dust, but for the moment no sufficient data are available.

Ibadov: Can you indicate the rate of generation of dusty matter during a collisional evolution of asteroids. I would like to know the relative role of asteroids and comets in maintaining the zodiacal dust cloud?

Zappala: Such process we did not consider.

Farinella: As regards the production of dust by collisional evolution of asteroids, the work by R. Greenberg, S. Dermott and others on the solar system dust bands discovered by IRAS has shown that comminution of the present asteroids by impacts provides the correct order of magnitude for the dust production rate.

Harris: In the size range $\approx 100$ km diameter, there appears to be a subgroup of very slowly rotating asteroids. These objects are perhaps tidally evolved binary systems, which originated by disruptive collisions such as you describe.

Knežević: What are the velocities that you compare in the first couple of your figures? Are these the projectile velocities?

Paolicchi: The velocities are those of ejected fragments, as a function of size. While the trend is absolutely significant, the numerical values could be scaled (with rotation and binding energy) to different values, to fit the experiments (as in the figure) of the asteroids.
It is a notorious fact that any analytical theory of asteroid motion, based on the usual development of the disturbing function into a power series truncated at some order/degree, can provide results of only limited accuracy. The uncertainty of derived mean and proper elements, frequencies and phases of free oscillations etc. depends very critically just on the order (with respect to the perturbing mass) and degree (power of eccentricity and inclination) of the terms in the disturbing function where the truncation takes place. However, although being of crucial importance for the applicability and reliability of a given theory, these uncertainties were so far known only to an order of magnitude at best, the amount of the residual error being usually estimated on the "first neglected term magnitude" basis. Another important consequence of this situation is that one does not explicitly know for how large eccentricities and/or inclinations the theory still provides a meaningful outcome — i.e. results of acceptable accuracy.

In the paper of Knežević et al. (1987), it has been shown that the second order - fourth degree theory of Yuasa (1973) provides fairly accurate mean elements (obtained when osculating elements are freed from short-periodic perturbations) even for asteroids of relatively high eccentricities and/or inclinations. Here we present some preliminary results of an attempt to define more precisely the threshold values of eccentricity and inclination for which this theory still provides mean elements of acceptable accuracy. The results of this first stage of investigation concern to accuracy of the mean semimajor axis only. The reason for this choice is obvious: providing we are far enough from resonances, the semimajor axis has no long-periodic perturbations, so that its mean value represents the final product of the perturbation analysis, and thus at the same time defines the corresponding proper value.

As regards the definition of "acceptable accuracy", this is more-or-less an arbitrary choice, depending mainly on the aim of the particular study, available computing equipment, etc. We adopted here as an acceptable accuracy threshold one that is usually posed as a requirement for a reliable classification of asteroids into families. Hence, we consider the result as accurate enough if for a certain set of initial conditions (osculating elements), the total remaining variation of the mean element (defined simply as the difference between the corresponding maximum and minimum of the derived mean values) in a long-enough time span does not exceed 0.001 AU for the semimajor axis. Note that the \( \Delta a \) ranges, within which the members of the major well established asteroid families are situated, extend typically to several hundreds of AU. The "long-enough" time span for short-periodic perturbations elimination is taken to be 500 yr.

What we did in practice is to integrate orbits of fictitious bodies located at various initial semimajor axes within the main asteroid belt by using the Everhart program (Everhart, 1985) in the four-body case, with Jupiter and Saturn as perturbing bodies. By fixing some small initial inclination (eccentricity) and varying the initial eccentricity (inclination), we obtained several sets of orbits to which the analytical procedure of elimination of short-periodic perturbations was then applied. Table I contains the initial osculating elements of the perturbing planets, as well as the corresponding initial values of the asteroid M, \( \omega \), and \( \Omega \), being the same for all our experiments. The quantities in parentheses are those small values of the initial eccentricity and inclination being assigned to one of the elements while the other was varied. Fig. 1 shows an example of how the total remaining variation of mean semimajor axis increases with the increase of initial inclination, while in Fig. 2 the critical values of eccentricity and inclination are shown for the nine different values of semimajor axis within the main belt.

The main conclusion that can be easily drawn from this investigation is that in the case of semimajor axis, providing we are far enough from resonances and at least one of the two significant elements - eccentricity and inclination - is small, Yuasa's analytical theory removes the short-periodic perturbations to a level accurate enough even for orbits of fairly high eccentricity or inclination (we recall that the median eccentricity for the numbered asteroid sample is about 0.16, and median inclination about 8° - see Knežević, 1982). The approach to the resonance, as expected, causes the abrupt decrease of the critical values, an example being given by the critical eccentricity value for \( a = 3.20 \) AU (that is rather close to 2:1 commensurability, located at 3.28 AU). The rapid diminution of the eccentricity and inclination critical values with the increasing distance from the Sun is perhaps not entirely meaningful. It is at least partly due to the simple criterion that we used to define threshold values. Although this, of course, does not affect the qualitative validity of our results, some physically better grounded criterion, like, for example, one based on the quantity \( K(A/Q) \), where \( K \) is a constant, that is connected with a change of the orbital velocity (Zappala et al., 1984), or some space preserving criterion based, for example, on Delaunay's variables, would by all means reduce the observed decrease significantly.

Let's state, finally, that the results presented here are to be completed: first, by increasing the number of points for which we have a precise determination of critical values, second, by investigating cases of simultaneous increase of eccentricity and inclination, and third, by adding to this analysis the results pertaining to other orbital elements. These three issues, however, are out of the scope of this paper, and are going to be studied in the frame of a future, more comprehensive analysis.
Fig. 1: An example of increase of the total remaining variation of the mean semimajor axis in the 500 yr time span; case of the small initial eccentricity (e = 0.01) and variable initial inclination. Scale unit on the y-axis is 0.001 AU, and represents the difference between the highest and lowest points on the corresponding plots.
Fig. 2: Critical values of the osculating eccentricity (full circles), above which the total remaining variation of the mean semimajor axis exceeds 0.001 AU. Solid lines represent the libration widths associated with the leading eccentricity term in the expansion of the disturbing function (as adapted from Dermott and Murray, 1983), and denoting the position and approximate extent of the Kirkwood gaps in the $a$ - $e$ plane. For the sake of simplicity, the critical inclinations (open squares) are also plotted here, but not the corresponding libration widths for the $a$ - $i$ plane.

Table I

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<th>$\omega$</th>
<th>$\Omega$</th>
<th>$i$</th>
<th>$e$</th>
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<td>274.918</td>
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<td>1.3064</td>
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<td>325</td>
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<td>0.01</td>
<td>2.2 - 3.2</td>
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PHYSICAL PROPERTIES OF ASTEROIDS

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ABSTRACT. In the last few decades new observational techniques have provided a wealth of physical information on several hundreds of asteroids. These objects are no longer seen as pointlike bodies, but have become small "worlds" with known sizes, mass shapes, surface compositions, rotational properties and collisional histories. The diversity of these "worlds" is astonishing: they range in size from less than 1 to 10^3 km, in spin period from a few hours to many days, in shape from nearly spherical to very elongated and/or irregular, in surface reflectivity from about 0.02 to 0.4, in composition from metal-rich and silicate rocks to volatile-rich carbonaceous assemblages. Of course there are many peculiar objects: asteroids with surface patches of different brightness and colour; bodies which have suffered internal heating and have developed a core/mantle/crust structure; asteroids converted by catastrophic impacts into gravitationally bound "piles of rubble"; objects with triaxial equilibrium figures or splitted into binary systems; outer-belt asteroids whose spectrophotometric properties are very much alike those of cometary nuclei. This paper reviews some of these recent findings, which are currently being interpreted in the frame of complex theoretical models for the formation and evolution of orbiting and collisionally interacting bodies.

1. INTRODUCTION

Among the known members of the solar system, namely the asteroids, the objects whose heliocentric or planetocentric orbits have been accurately determined, the asteroids represent by far the most numerous population. The number of catalogued bodies is now approaching 4000, about 97% of which orbit the Sun in moderately eccentric and inclined orbits lying in a large toroidal region between 2.1 and 3.6 AU from the Sun, the so-called "main asteroid belt". Their sizes are so small (typically, 100 km plus or minus one factor of 10) that even with the best ground-based telescopes they are seen as unresolved star-like objects (hence their very name). It is then understandable that until a few decades ago the asteroid population was considered to be interesting mainly as a "dynamical zoo", that is a collection of test particles whose (often peculiar) orbital motions had to be modeled by the techniques of celestial mechanics. As for their physical properties, the asteroids were thought to be just huge "stones", possibly generated by some primordial cataclysmic event like in Olbers' exploded planet hypothesis.

Today, the situation is entirely different. The asteroidal objects are still a topic of much current interest for celestial mechanicians, but a growing community of astronomers and planetary scientists is now studying the asteroids as a set of small but diverse "worlds", with their own physical, chemical and geological characteristics to be understood in the frame of a complex evolutionary scenario. In this review I shall try to point out some intriguing and far-reaching results of this recent research effort, trying at the same time to emphasize the implications on the processes to which these bodies have been subjected in the larger context of the origin and evolution of the solar system. The reader interested in the most technical aspects and in detailed descriptions of current research is invited to look into the "Asteroids" book published after the 1979 Tucson conference (T. Gehrels, ed., Univ. of Arizona Press, Tucson) and into the next, updated such book which is presently in preparation.

2. ASTEROID SIZES AND DENSITIES

Asteroids are generally darker and larger than it was thought 20 years ago, when the only available method to estimate their size was based on (quite arbitrarily) assuming some average albedo value. Most diameters are now determined by radiometry, i.e. by deriving the albedo from the comparison between the brightness at visible wavelengths and that at the infrared wavelengths where the body emits thermal radiation. This technique was first applied by using ground-based telescopes and, more recently, by exploiting space-based observations like those carried out by the IRAS satellite in its systematic survey of the sky at infrared wavelengths (Matson, 1986). The radiometric technique can be made quantitative only by assuming a model for the thermal behaviour of a rocky, regolith-covered spinning object, but this model dependence can be calibrated by comparing the resulting albedos and diameters with those provided by other methods, like polarimetry (the polarization vs. solar phase angle relationship has been shown to correlate with laboratory measurements of albedo for a variety of rocky minerals), speckle interferometry, radar and the sporadic observations of stellar occultations. As a result, the radiometrically determined diameters are now thought to be generally accurate at the 5% level.

The largest asteroid, Ceres, is about 950 km across. There are about 30 asteroids larger than 200 km, 250 larger than 100 km, 700 larger than 50 km. The IRAS derived size distribution, in the range where the observational sample is almost complete, is shown in Fig. 1. At sizes between 1 and a few tens of km, we have only the very partial (and, possibly, bias-
collisional fragmentation, which predicts a power-law distribution contained in the few largest bodies, with the largest experiments (Fujiwara, 198G). Distributions have also been observed for the equilibrium mass distribution with \( q^{\frac{11}{6}} \) (Dohnanyi, 1970; Hufner and Mukhopadhyay, 198G). Similar evolution of a population of bodies subjected to disruptive iiapact events. Although a more detailed analysis of the observed size distribution is affected) sample of the Palomar-Leiden Survey (PLS), carried out in the late 60s (Van Houten et al., 1970). These data are usually represented via a power law distribution, where the number \( N \) of bodies in the mass range \( (m, m+dm) \) or, equivalently, in the diameter range \( (D, D+dD) \) is assumed to be proportional to \( m^{-q} \) or \( (2^{-q})dD) \). The PLS best-fitting value for the exponent \( q \) is 1.65, but at larger sizes there are 'bumps' and other departures from a straight line in a double-logarithmic plot of the distribution (like that of Fig.1), which appear to vary with heliocentric distance and taxonomic class (Zellner, 1979). From Fig.1 we can notice a clear excess of asteroids with diameters near 100 km, which may be related to the fact that at about this size the self-gravitational binding becomes important with respect toaterial strength, changing the response to disruptive impact events. Although a more detailed analysis of the observed size distribution is possibly premature, its general features compare satisfactorily with simple theoretical models for the evolution of a population of bodies subjected to collisional fragmentation, which predicts a power-law equilibrium mass distribution with \( q = 11/6 \) (Dohnanyi, 1970; Hufner and Mukhopadhyay, 1986). Similar distributions have also been observed for the fragments generated in laboratory impact fragmentation experiments (Fujwara, 198G).

It is important to notice that, whenever \( q \) is less than 2, most of the mass in the distribution is contained in the few largest bodies, with the largest

one (for the asteroids, Ceres) allowing alone for a fraction \( (2-q)/(q-1) \) of the total mass. Thus the total mass in the asteroid belt is not much larger than the mass of Ceres, a plausible estimate being half a thousandth of the Earth's mass (or some 5% of the mass of the Moon). If the original density of solid material in the solar nebula varied evenly with solar distance, then the proto-asteroidal material had to be depleted by a factor of the order of \( 10^7 \), much more than implied by the resonance-related gaps observed today. A possibility is that mutual disruptive collisions gradually comminuted the original planetesimals to dust, subsequently removed by non-gravitational effects. However, recent investigations (Davis et al., 1985; Farinella et al., 1986) have shown that such an intense collisional depletion is not consistent with observational constraints inferred from the preserved basaltic crust of Vesta, the abundance of dynamical families and the rotational properties of intermediate size asteroids. Alternative theories relate the mass depletion to powerful resonant interactions occurred in the solar nebula, possibly sweeping through the primordial asteroid belt, or to gravitational encounters with large, planetary-mass planetesimals coming from Jupiter's accretion zone. The same primordial processes have probably stirred up the asteroid orbits, increasing their eccentricities and inclinations and leading to average relative velocities (about 5 km/s) which allow disruptive collisions.

Direct measurements of individual asteroid masses and densities are still very scarce. For the few largest asteroids, the analysis of gravitational perturbations on other asteroids and on Mars (Schubart and Matson, 1979) has yielded masses affected by large error bars, which just allow to conclude that their densities are consistent with typical values for rocks (\( \approx 3 \text{ g/cm}^3 \)) or for carbonaceous-chondrite meteorites (\( \approx 2 \text{ g/cm}^3 \)). The latter value is close to the Viking-measured density of the Martian satellites. For a few objects, nearly equilibrium shapes have been inferred from their rotational properties (Farinella et al., 1981), leading to density estimates which cluster between 2 and 2.5 g/cm\(^3\). Probably, however, density data reliable and accurate enough for constraining the composition and internal structure of asteroids must await direct measurements carried out during spacecraft encounters.

3. ROTATIONAL PERIODS

Most available data on the asteroid rotations and shapes come from lightcurve photometry, a traditional astronomical technique which in the last 15 years has been applied by a growing number of observers worldwide. In spite of occasional ambiguities, the lightcurve periodicity directly yields the spin period of the asteroid, and periods for some 400 objects are now available. The average period is of about 12 hr, but a significant dispersion is present and periods as short as 3 hr or as long as weeks have been observed. Statistical analyses carried out in the last decade (e.g., Farinella et al., 1981; Dermott et al., 1994) have evidenced slight, but physically relevant correlations of the spin period with the asteroid size and taxonomic class. As shown in Fig.2, a running-box plot of the average rotation rate vs. diameter (the

![Figure 1](image-url)
upper and lower curve showing the $1 - \sigma$ dispersions of the adopted samples), there is a significant drop of the spin rate at a diameter of about 100 km with respect to larger bodies, while for smaller asteroids there is a much greater dispersion about somewhat shorter mean periods. Moreover, as shown by Fig.3 (obtained for a sample of about 200 asteroids, chosen in order to minimize observational biases), the spin rate distribution is not fitted well by a 3-dimensional Maxwellian curve, such as would be expected from an isotropic, 'kinetic'-type collisional process, but shows a significant excess of slow rotators especially at small sizes (less than 100 km). In other words, there are definitely too many asteroids with long rotational periods than it would be expected stochastically, and it has been suggested that in some cases tidal despinning by a satellite might have occurred, while in others precessional motions (again forced by a satellite) might cause the most prominent brightness variations instead than pure spin. Another intriguing observation is that the metal-rich M-type asteroids have a significantly faster average rotation than the more numerous C and S classes, possibly implying markedly different bulk properties (like density or impact strength). Similar subtle but interesting differentiation have recently pointed out by Binzel (1987) between two of the most populous Hirayama's dynamical families, the Eos and Koronis families. Families are thought to be the likely outcomes of the collisional fragmentation of sizeable asteroids, and possibly the different distribution of spin rates just 'remembers' the rotation of their parent bodies. Another intriguing result is that the rotation rates of Earth- and Mars-crossing asteroids (available for some 25 objects, of size of the order of 1 km) have a very flat, possibly bimodal distribution, with several slow rotators which might just be extinct comet nuclei, for which torques due to outgassing phenomena could have affected the initial rotation (although the few available data on the spins of comet nuclei do not show a clear overabundance of slow rotators with respect to small main-belt asteroids).

Modelling the collisional evolution of the asteroid spins is a very difficult task. A simple analytical theory proposed by Harris (1979) derives a differential equation for the evolution of the rotation rate analogous to that which governs Brownian motion: a positive (spin-up) term is mostly due to the rare nearly-catastrophic collisions, and a negative (spin-down, or 'drag') term is caused by the frequent small scale impacts. Since the two terms have a different dependence on the pre-existing spin rate, the theory implies that an equilibrium spin rate exists. This equilibrium value depends on several poorly known parameters, like the mean density of the asteroid, the characteristic exponent $q$ of the projectile mass distribution and the fraction $f$ of the projectile's kinetic energy delivered to fragments after a catastrophic breakup. If all these parameters were independent on size, the equilibrium spin rate would also be independent on size down to diameters of a few km, while smaller bodies should spin faster and faster. The equilibrium spin rate is also proportional to the square root of the density, in agreement with the faster rotation of M-type (probably metal-rich) asteroids. However, if the 'anelasticity coefficient' $f$ is at most of the order of $0.1$, as observed in laboratory impact experiments, the theory predicts equilibrium spin periods shorter by at least a factor 3 than the observed average period (Davis et al., 1979). A number of reasons have been suggested to explain this discrepancy, as well as the size dependence of the spin rate shown in Fig. 2. First, some of the parameters (for instance, $q$) are known to vary with size. Second, relaxation to the equilibrium spin rate is slow unless the asteroid is able to withstand even the largest collisions without strong mass loss. This is due to the fact that the theory assumes (for lack of better hypotheses) that the spin rate is unchanged during a catastrophic fragmentation event. However, it appears more likely that a complex partitioning of angular momentum to fragments leads to a change in the average spin rate in this case, including some definite size dependence as found in laboratory experiments by Fujiwara and Tsukamoto (1981). Since for most asteroids there is no time for relaxation between two successive breakups, they should reflect the spin rate distribution arising from the breakups rather than the equilibrium value. Third, the theory assumes that the asteroids have spherical shapes, but for elongated bodies the higher moment of inertia could partially compensate for a longer spin period. Fourth, as already mentioned, tidal despinning might have been fairly frequent, and on the other hand for self-gravitating objects the possibility of binary fission implies a lower rotational stability limit at a period of about 4 hr. Fifth, Dobrovolskia and Burns (1984) have pointed out an additional despinning mechanism, based on the fact that ejecta from crater-forming impacts can preferentially escape in the direction of the asteroid rotation. This effect only operates in
the intermediate size range (Fig. 4, case (b)), since for large asteroids most of the ejecta fall back (case (a)), while for small bodies nearly all the ejecta escape (case (c)). This list of problems with Harris' theory can be seen as just an example of the complexities and subtleties which have to be accounted for in order to quantitatively model the evolution of the asteroid physical properties.

4. SHAPES AND POLES

Additional observational constraints on the collisional evolution process are provided by the knowledge of asteroid poles and gross shapes. The procedures used for shape and pole studies are closely related, because every shape determination is based on some assumption on the orientation of the body. For instance, when the aspect angle (between the polar axis and the line of sight) is 90°, if one assumes that the asteroid albedo is uniform, that the brightness is proportional to the geometric cross section ('geometric' scattering of light) and that the shape fits well a triaxial ellipsoidal figure of semiaxes \(a \geq b \geq c\), then the lightcurve amplitude \(A\) is simply given by \(2.5 \log(a/b)\); thus this parameter provides an estimate of the equatorial elongation of the asteroid. On the other hand, for the same shape but at smaller aspect angles the amplitude is also smaller, and of course it vanishes when the object is seen pole-on. As a consequence, when the polar axis is unknown, the lightcurve amplitude can be taken only as a statistically meaningful indicator of the shape; even when the pole is known, the simplifying assumptions about the ellipsoidal shape, the uniform albedo and the geometric scattering law make the shape determinations just very approximate estimates. For instance, large-scale and strong albedo contrasts are generally ruled out by the results of polarimetric observations (Dollfus and Zellner, 1979). However, when the lightcurve displays a complex morphology (instead than the quasi-sinusoidal form with two maxima and two minima per cycle caused by an ellipsoidal shape) and a small amplitude (of the order of 0.1 mag), albedo patches on the surface may well be responsible of the observed variations.

A statistical comparison between the observed lightcurve amplitudes of asteroids and those which would be associated with the irregular shapes of fragments from laboratory high-velocity impact experiments has been carried out by Catullo et al. (1984). While for most asteroids larger than 200 \(Km\) many lightcurves are available, obtained at different oppositions, this is not the case for many asteroids smaller than 100 \(Km\). Thus in the former case the maximum observed amplitudes can directly be compared with the 'equivalent amplitudes' \(2.5 \log(a/b)\) computed from fragment shapes measured in the laboratory, while in the latter case one has to assume that the amplitudes (both for asteroids and for fragments) are referred to a 60° aspect angle, the average value for a set of isotropically oriented polar directions. Fig. 5 shows the results: the amplitude distributions are qualitatively similar for fragments and small main-belt asteroids (among the planet-crossing objects several bodies have been observed much more elongated than could be predicted from the \(b/a\) distribution of the fragments), but a strong difference is found for larger bodies, which show a much narrower peak at low amplitudes and just a 'tail' at high amplitudes.

These findings are hardly surprising. The collisional evolution models (Farinella et al., 1982; Davis et al., 1985) predict that most small asteroids are just fragments from catastrophic disruption events. Their escape velocity is lower than the
typical ejecta velocities, so that they could not reaccumulate most of the material ejected by impacts, and their irregular shape is related to the fact that the solid-state material strength allows them to 'remember' the features moulded by repeated energetic collisions. On the contrary, most large asteroids have probably relaxed to quasi-equilibrium shapes, either because they were primordially melted, or because they were converted by the collisional process into gravitationally bound 'rubble piles', i.e., agglomerations of fragments and debris comminuted by impacts but reaccreted by the target body (because of its relatively high escape velocity - 100 to 150 m/s for a 200-km sized asteroid). A 'pile of rubble' has by definition a negligible tensile strength, and if the individual fragments are small enough and no significant density variation is present, its surface should roughly fit one of three types of 'liquid' equilibrium figures, depending on the rotational angular momentum $L$: (i) for $0 < L < 0.30 (GM^3)^{1/2}$, an oblate Maclaurin spheroid, with $a = b > c$ and $c/a$ decreasing for increasing spin rates; (ii) for $0.30 (GM^3)^{1/2} < L < 0.39 (GM^3)^{1/2}$, a triaxial Jacobi ellipsoid with $a > b > c$ and $a/b$ increasing for increasing angular momenta (but for decreasing spin rates, due to the rapid change of the momentum of inertia); (iii) for $L > 0.39 (GM^3)^{1/2}$, a fission binary system, with nearly-contact components and synchronized spin and orbital periods.

Maclaurin spheroids probably account for the large fraction of small amplitude objects among the large asteroids (including the three largest bodies, Ceres, Pallas and Vesta). Jacobi ellipsoids were first proposed by Farinella et al. (1981) as an explanation for the observational fact that in the 150 to 300 km diameter range several large amplitude objects exist with spin periods in the range from 4 to 6 hr. yielding the appropriate amount of angular momentum for reasonable densities ($\sim 2 \text{ g/cm}^3$). Fig. 6 is another running-box plot showing that for bodies larger than 150 km high amplitudes are indeed correlated with short periods (this correlation does not exist for smaller bodies). Finally, nearly-contact equilibrium binary models have been proposed by Weidenschilling (1980), Leone et al. (1984) and Cellino et al. (1985) to explain several cases of very high amplitude lightcurves, like for 624 Hektor (the largest Trojan asteroid) and 216 Kleopatra. Fig. 7 is a plot derived by Leone et al., which shows the regions in the maximum amplitude vs. spin rate plane were Jacobi ellipsoids and equilibrium binaries are possible, the dashed zones corresponding to the realistic density range between 1.5 and 4.0 g/cm$^3$. The $q$ scale refers to different values of the mass ratio for the binary models. The positions of several asteroids in this plane are shown by triangles (100 km $< D < 150$ km), squares (150 km $< D < 200$ km) and circles (D $> 200$ km); two peculiar objects with D $< 100$ km (43 Ariadne and 44 Nysa) are represented by asterisks. Open symbols mean that the amplitude is probably lower than the maximum one, because few observations are available. As shown by this plot, were the equilibrium shape of these asteroids accurately known, a precise estimate of their density would also be possible. For instance, the equilibrium binary model for Hektor implies a density of about 2.5 g/cm$^3$.

Of course, a pile of rubble can relax to an equilibrium figure only if the irregular shape of the largest reaccumulated fragments is smoothed out by a thick regolith layer formed by finer debris. For the usual power-law mass distribution of fragments, it is easily shown that the fraction of the total mass contributed by fragments of mean size less than $k$ times the size of the largest fragment is $k^{(q-3)}$, with the exponent $q$ of the differential mass distribution approaching 2 when the shattering mechanism provides significant amounts of energy in excess of the threshold needed for fragmentation (see e.g. Hartmann, 1969). This is probably the case for asteroids, which have to suffer a large number of small, subcatastrophic collisions before a disruptive impact by a massive projectile occurs. The formula given above yields, for $q=1.8$, 10% and 25% of the mass.
contributed by fragments of size less than 50 and 10 times that of the largest object, respectively. For \( q \approx 1.3 \), these percentages are 31% and 50%. Thus it seems likely that the amount of small fragments is in most cases sufficient to prevent the appearance of large-scale irregularities on the surface of the 'piles of rubble'. It has been argued that even finely fragmented bodies should maintain some topographical features, because a loosely cohesive material can support significant static slopes, just as it is the case for repose maintained on a sand-box. However, the rubble-pile asteroids would be continuously shaken by small-scale impacts, causing redistribution of debris towards depressed areas both by direct production of ejecta and by seismic disturbances favouring downhill movements of the loose material (indeed, widespread evidence of these phenomena has been observed in the Viking images of the Martian moon Deimos).

As concerns poles, several techniques are now available which yield reliable results when based on sufficient data. The first method to determine from lightcurve data both shapes and polar directions is known as 'amplitude-aspect' method (Zappala et al., 1983) and is based on the fact that both the lightcurve amplitude and the absolute magnitude at maximum apparent area are functions of the aspect angle. Therefore the latter can be derived for each apparition of the asteroid by making some simplifying assumptions on the shape of the body (triaxial ellipsoid spinning about the shortest axis), the scattering law of its surface ('geometric'), the influence of nonzero phases and obliquities on the amplitudes (considered as negligible for observations at phases \( < 10° \)). Recent work has shown that these assumptions can be relaxed without affecting the final solutions for the polar directions by more than 5° or 10°. A second method, called 'photometric astrometry' (Taylor, 1979), assumes that the time of occurrence of a given feature in a lightcurve (e.g., an extremum) corresponds to the time of transit of a specific meridian on the asteroid surface on the line of sight. If lightcurves taken at several apparitions well spaced in ecliptic longitude are available, the direction of the polar axis and the sense of rotation are derived by minimizing the residuals of the calculated times of transit of a meridian with respect to the actual occurrences of the specific lightcurve feature. Both these methods clearly work better for objects of very elongated shapes and simple lightcurve morphology, but they are complimentary in that the former one yields better results if the pole lies at time along the line of sight, while the opposite is true for the latter one. Therefore, when many observations are available, the final accuracy can be improved by coupling the two techniques (Magnusson, 1983). Another potentially fruitful technique is radar. From the observed Doppler bandwidths one gets a direct measurement of the range of radial velocities on the asteroid surface, and this depends on the size, spin period and aspect of the asteroid. So far, these methods have been applied only to a few tens of bodies, and the sample is not yet large enough for meaningful statistical conclusions to be inferred. Clearly, the extent to which the polar directions are isotropically distributed on the celestial sphere (possibly, as a function of the size of the bodies) is potentially an important constraint for collisional evolution models, since any anisotropy could be interpreted as a record of the 'initial' (i.e., accretionary) rotational states not yet randomized by collisions.

Is it possible to derive from lightcurve observations some different and more complex 'mixture' of results about poles, shapes and albedo variations on the asteroid surfaces? The traditional negative answer is based on Russell's (1906) study, which mathematically proved that lightcurves cannot provide unique solutions for the shape and the albedo distribution of planetary bodies; even assuming a known convex shape (and a known polar direction), an infinite number of albedo distributions can always match the observed lightcurves. There are two reasons for that: (i) unless the polar axis lies on the orbital plane, only the brightness difference (and not the absolute albedo values) between the two polar regions can be actually inferred; (ii) even so, the lightcurve data do not allow the odd spherical harmonics of the albedo distribution of order \( > 1 \) to be estimated at all. Therefore, any detailed 'map' of an asteroid surface derived from lightcurves would be totally meaningless. However, Occam's razor can be used to constrain a priori the choice of the model to be fitted with the data in such a way to obtain some general information on the average, large-scale distribution of albedo. For instance, Cellino et al. (1987) have fitted all the available lightcurve data for Vesta with a simple model in which the shape was assumed to be spheroidal (with the flattening treated as a solve-for parameter) and only two distinct surface regions with two different albedo values and a geometrically simple border were assumed to represent the large-scale features of the albedo distribution (this latter choice rules out both sources of arbitrariness found by Russell). The results of the fitting procedure represent an almost-unique solution for the parameters representing the albedo contrast, size and position of the 'albedo regions', the polar coordinates and flattening of the asteroid. Fig. 8 shows a view of the Vesta model leading to this solution; if the derived flattening corresponds to the equilibrium shape of a nearly homogeneous body, a density of 2.48±0.3 g/cm\(^3\) can also be inferred. The regular shape and the existence of large-scale albedo variations are also consistent with spectroscopic studies suggesting that Vesta's surface is covered by extensive lava flows of basaltic composition, as a consequence of an early partial melting and differentiation of the interior. Vesta is probably a 'primordial', unshattered asteroid, whose thin basaltic crust displays some mineralogically distinct regions.

5. TAXONOMY AND COMPOSITIONS

The conclusions quoted above about Vesta's composition and history are not an isolated case. In the last two decades an intense observational effort has shed light on the problem of asteroid compositions, which have been found to be very diverse and to hold important clues to primordial processes occurred in the solar nebula and during the early stages of accretion and differentiation of planetary embryos. The main source of information is spectral analysis of reflected sunlight, but other techniques like radiometry, polarimetry and planetary radar have yielded significant contributions. These data have been often
interpreted via direct comparison with the properties of mineralogical assemblages found in the different meteorite types.

A very apparent difference among diverse types of asteroid surfaces is evidenced by the distribution of albedos. When the observational bias against darker objects is accounted for, some 75% of the asteroids are found to be very dark, with average albedos of ~0.04. A distinct group of bodies has moderate albedos of about 0.15, with few asteroids lying in between but a tail of 'bright' bodies having albedos up 0.4 and more. A better discrimination is possible if the albedo data are coupled with spectrophotometry data, yielding the behaviour of the reflection spectrum over a wide wavelength interval. Some absorption bands are unequivocally diagnostic of the presence of silicates, water ice and hydrated minerals, but in many cases these prominent features are lacking and any inference on the mineralogical composition must be seen as very conjectural.

Clustering statistical techniques have been applied to a set of suitably chosen parameters, considered a priori as potentially diagnostic of composition, in order to define the so-called taxonomic types. The latest work in this direction (Barucci et al., 1987) has shown that every classification is non-unique, but depends on the confidence level at which the types are separated. However, the principal types coincide in the classifications derived by different methods, so that they can be considered as reliably identified and defined, and correspond very probably to markedly different mineralogical compositions. For instance, C-type asteroids have a very low albedo and a flat spectrum throughout the visible and the near-IR; they are very probably similar in composition to carbonaceous chondritic meteorites, which are very primitive mineral assemblages subject to no or very little metamorphism after their condensation. D-type objects are also dark but have very red spectra, suggesting the presence of low-temperature organic compounds. These objects are similar to many low-albedo, reddish small bodies found in the outer solar system, including some comets observed at low activity and a few small satellites (e.g., Phoebe). S-types have relatively high albedos, and their spectra show absorption bands due to silicates like pyroxene and olivine. It is debated whether their likely meteorite analogs are the stony-iron meteorites (probably derived from the core-mantle interface of differentiated parent bodies), or the ordinary chondrites, interpreted as assemblages of primitive nebular grains of different compositions, subsequently heated and metamorphosed only modestly. The M-type asteroids have albedos of about 0.10, with slightly reddish, straight spectra, suggesting a significant content of nickel-iron metal. It is possible that they are akin to iron meteorites, hence that they represent pieces of the cores of differentiated precursors. Recent radar observations of the large M-type asteroid 16 Psyche (Ostro et al., 1985) confirm this interpretation, and suggest that this body is just the collisionally stripped metallic core of a large parent asteroid, of about the same size as Vesta. In this case, it would be difficult to understand why two objects with similar initial structures underwent a very different evolution as a consequence of the collisional process (Chapman, 1986).

Of great interest is the fact that different taxonomic types are preferentially located at different heliocentric distances. Fig. 9, adapted from Gradie and Tedesco (1982), shows the distribution of types vs. semimajor axis for about 650 objects, as compared with the number distribution for a bias-corrected sample of about 1400 asteroids in the same semimajor axis range (the dashed histogram corresponding to taxonomically classified objects). This orderly progression of types is usually interpreted as reflecting variations in the composition of the material which condensed into solid grains in the solar nebula, variations related in a
predictable way to the temperature decrease with solar distance. It is also interesting to note that the most primitive types (corresponding to least metamorphosed material) tend to occur in the outer belt, and that most asteroids in this outer region resemble in a significant way the properties of comet nuclei (Hartmann et al., 1987).

6. FUTURE RESEARCH DIRECTIONS

Many important research programs on asteroid physical properties are under way or planned for the near future. These include new spectrophotometry and lightcurve observations which should extend to smaller sizes the presently available data banks; extensive application of relatively new techniques like radar and speckle interferometry; new laboratory simulations and impact experiments as well as theoretical modelling of the impact events. Space-bound observations have been recently carried out by IRAS, which has provided an extensive and least-biased survey on asteroid sizes and albedos, and will be carried out by the Hubble space telescope, which has the potential of obtaining images of asteroid surfaces at a resolving power corresponding to a few tens of km. However, many basic uncertainties and open problems exist which cannot be solved by Earth- and near-Earth-bound observations and studies, but need close-up investigations performed by dedicated space missions. For instance in situ density and composition determinations as well as high resolution imaging for just a few (suitably selected) asteroids would be exceedingly valuable. Since space missions have explored to date (or will in a few years) all the major planets, their satellite and ring systems and even some comets, asteroids are the next obvious target to be considered with a high priority.

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DISCUSSION

Kristensen: Russell proved in 1906 that we cannot distinguish between shape and albedo variations. Is your assumption that the lightcurve of Vesta is dominated by spottness supported by variations of the color index? Farinella: There are polarimetric observations of Vesta showing a periodicity equal to that of the lightcurve. This strongly suggests a heterogeneity of the surface. Moreover, Vesta is a 500-km sized object, and it is unlikely that its overall shape is irregular (compare, e.g., with Mimas, Enceladus or Miranda, which have the same size and show nearly-equilibrium shapes). On the other hand, Russell’s result is valid for general convex shapes or albedo distributions on the surface. If one constrains the model by choosing an axisymmetric ellipsoidal shape and a two-patches albedo distribution, the photometric data can be fitted with no ambiguity. Of course, this means that only large-scale albedo variations can be detected from these data (see Cellino et al., 1987 , Icarus 70, 466). Grön: I wonder how reliable, i.e. how unambiguous, is the result you get. The unknown properties for which you have to solve are the shape, the albedo pattern, and the rotational state.
Harris: Russell (1906) demonstrated that certain conclusions can be drawn from a light-curve observed from an equatorial aspect and at low phase angle: 1) The presence of any odd harmonic higher than the first indicates non-geometric scattering; 2) The presence of a first harmonic indicates non-geometric scattering (unlikely) and/or albedo variegation (almost certainly); and 3) A light curve with no odd harmonics can be due to shape only, but may also be due to albedo variegation and non-geometric scattering. He also noted that it is impossible to deduce the pattern of albedo variegation from the lightcurve. Keeping these items in mind, the evidence is very strong in favor of some pattern of albedo variegation on Vesta (i.e., the first harmonic is present at all observed aspects and phase angles). Beyond a simple statement that it exists, any attempt to derive a map or to make physical interpretations based on a constrained solution for the pattern of variegation is very dangerous.
EFFECTS OF NON-TRIAXIAL SHAPE ON THE DETERMINATION OF THE ASTEROID SPIN AXIS DIRECTION VIA THE AMPLITUDE-MAGNITUDE METHOD

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At present, the Amplitude-Magnitude (AM) method is largely applied for determining the spin axis direction of asteroids; such a method gives results which are in general in a good agreement with those obtained by means of essentially different methods. However, one of the critical assumptions of the AM method is that asteroids are modelled as triaxial ellipsoids with semiaxes \(a>b>c\). Although such an hypothesis appears reasonable for large objects on the basis of physical considerations about their expected equilibrium shapes, very irregular figures are more plausible for smaller objects, probably dominated by solid-state forces. Therefore, it is worth-while to study the influence that deviations from a purely triaxial ellipsoid shape can have on the derived spin axis direction. For this purpose, a numerical program has been developed in order to compute the lightcurves of irregularly shaped objects at given aspect angles. The present paper reports some preliminary results concerning the uncertainty of the rotation axis direction of asteroids when non-triaxial shapes are considered.

1. INTRODUCTION

During last decade, special efforts have been devoted to the determination of the spin axis direction of asteroids. In fact, the knowledge of this parameter for a large number of objects can provide important information about the origin and the evolution of the minor bodies in the Solar System.

The problem of the determination of the spin axis direction of asteroids has been solved by different techniques, but mainly using observational parameters extracted from the lightcurves of the objects. Among the main methods, the so-called Amplitude-Magnitude (AM) method (Zappala, 1981; Zappala et al., 1983), is based on the assumption of a triaxial ellipsoid shape for the objects to be studied. Such an assumption has been proved to be plausible in the case of large objects (diameter \(D > 150\) km), for which self-gravitation can play a fundamental role in determining their equilibrium shapes (Farinella et al., 1981).

On the other hand, deviations from regular triaxial ellipsoid shapes should be expected for small asteroids, thought to be rocky outcomes of catastrophic events, whose shape are mainly dominated by solid-state forces. Even if very irregular shapes are in principle recognizable on the basis of the morphology of the observed lightcurves, how they can affect the determination of the rotation axis is still an almost unknown problem.

The aim of the present analysis is to evaluate the errors introduced by applying the AM method to objects which largely differ from regular triaxial ellipsoids. This study assumes a particular importance mainly in consideration of future applications of this method to a large set of objects of moderate size, as a larger number of photoelectric observations will become available.

We should notice that the presence of albedo features on asteroid surfaces can be another source of errors in the determination of the poles; we will neglect this effect in the present paper, where we concentrate on the shape effect only. The effects of albedo features have been analysed, for instance, in a paper concerning the asteroid 4 Vesta (Cellino et al., 1987).

2. THE NUMERICAL PROGRAM

In order to analyse systematically the influence of deviations from a regular triaxial ellipsoid shape, it is necessary a general model for which the variation of a few parameters can describe a wide range of irregular but "realistic" shapes. For this purpose, we adopted a model formed by merging together eight different octants of ellipsoids having different semiaxes, provided that adjacent octants have equal semiaxes. As "reference" body we have chosen a triaxial ellipsoid having semiaxis ratios \(b/a = 0.7, c/a = 0.5\). These values are in agreement with the results obtained in laboratory experiments of catastrophic impacts, in which it has been shown that the creation of fragments with this mean shape seems a very general rule (e.g., Fujikura, 1986); furthermore, this tendency is consistent with statistical approaches on real asteroids (Catullo et al., 1984). On the other hand, such a shape gives quite large lightcurve amplitudes for aspect angles \(\alpha\) at 90° (\(A \sim 0.4\) mag).

The deformations of the reference object have been carried out in the following way: taking \(a=1\) as length unit, and fixing as constants the sums of the semiaxes \(2a = a_1 + a_2 = 2\); \(2b = b_1 + b_2 = 1.4\); \(2c = c_1 + c_2 = 1\), we have varied, separately and not, the ratios \(a_1/a\), \(b_1/b\), \(c_1/c\) from 0.1 to 0.7, obtaining a large set of different shapes.

The simplest way to compute the corresponding lightcurves is to approximate the surface by a polyhedron formed by a number of plane facets. Obviously, the approximation is better increasing the number of facets. As an example, Fig. 1 shows an object having \(a_1/a=0.50, b_1/b=0.45, c_1/c=0.30\), seen at 45° aspect angle. The computation of the total apparent area (i.e., the "luminosity") is performed adding together the contributions of all the small plane facets constituting the polyhedral surface: each of them can be illuminated or not, visible or not, and presents a varying cross-section to the observer, as the rotation of the object around its axis changes the configuration of the facets. Thus, a lightcurve is obtained repeating the calculation at different rotational angles from 0° to 360°.
It is well known that the observed lightcurves of real asteroids depend also on the scattering of the reflected light on the asteroid surface. This effect depends in a complicated way on parameters like surface albedo, roughness, etc., and it is more pronounced as the phase angle increases. On the other hand, when $\alpha = 0^\circ$, the effect is quite negligible especially when low-albedo objects are considered (Lupishko et al., 1983; French and Veverka, 1983). In real asteroids, the effect is quite negligible, provided a certain number of lightcurves at different phases are available.

In this preliminary stage of our study, we have assumed always $\alpha = 0^\circ$, and we have neglected the scattering effect, so that, for a given model, the resulting lightcurves will depend only on the aspect angle $\xi$.

3. ORBITAL PARAMETERS AND POLE CALCULATION

Before to perform the simulations, it has been necessary to determine the relationships connecting the ecliptic coordinates with the aspect angle $\xi$. To do so, the unit axis direction of the object and its orbital parameters have been fixed. For what concerns the latter, we have chosen values typical of main belt asteroids: $\omega = 0^\circ$, $e = 0.1$, $i = 10^\circ$, $\Omega = 100^\circ$; the pole coordinates were fixed at $\lambda_o = 45^\circ$, $\beta_o = 45^\circ$.

To perform the simulations, the pole determination is performed on the basis of lightcurves obtained at different positions of the asteroid on the celestial sphere. The knowledge of the observed lightcurve amplitudes and magnitudes at maximum, and of the corresponding coordinates $\lambda$ and $\beta$ of the asteroid allows to compute the aspect angle $\xi$, at each observation, and to derive the pole coordinates $\lambda_{oc}$ and $\beta_{oc}$. In order to reproduce this situation in our numerical simulations (in which, obviously, the aspect angle is known "a priori" and allows to compute the lightcurve of an object at any position), we have chosen four values of $\xi$ conveniently spread over the celestial sphere corresponding to aspect angles ranging from $20^\circ$ to its minimum value. Then, the corresponding lightcurves were obtained by the numerical program, and the amplitude vs longitude and (MAX) vs longitude relationships were used as input for the application of the AM method (Zappalà et al., 1983). In such a way the values of the coordinates of the "computed" pole (and of the semiaxis ratios) could be compared with the "real" assumed values. The discrepancies allow to evaluate the sensitivity of the AM method to the changing shape of the model.

4. RESULTS AND DISCUSSION

Table I lists the cases we have considered in our simulations; the columns give: the semiaxis ratios $a/a$, $b/b$, $c/c$, the coordinates of the computed poles, and the values of the error $\Delta$ defined as

$$\Delta = \left( (\lambda_{oc} - \lambda_o)^2 + (\beta_{oc} - \beta_o)^2 \right)^{1/2}$$

It is easy to see that the computed pole differs more from the true pole as the shape becomes more irregular, as obviously expected. However, the situation is more complex in the sense that the solutions are sensitive in different ways to strong deformations of the object along different axes. For instance, modifying the $a/a$ ratio gives in general smaller errors than modifying the $b/b$ ratio.

Except some cases (discussed later) in which it was not possible to find the pole on the basis of the given lightcurve amplitudes and magnitudes, we see that in general the errors are not huge, the parameter $\Delta$ ranging from a few degrees up to $20^\circ-30^\circ$ in the worst cases. However, in these cases the shape of the object is in general so far from a regular triaxial ellipsoid that the morphology of the resulting lightcurves differs sensibly from what has to be expected for a regular ellipsoid: it follows that one can easily know "a priori" that the application of the AM method should be considered mostly indicative, and comparison with different methods for pole determination should be very auspicious for a reliable solution.

Table I

<table>
<thead>
<tr>
<th>$a/a$</th>
<th>$b/b$</th>
<th>$c/c$</th>
<th>Computed Pole</th>
<th>$\lambda_{oc}$</th>
<th>$\beta_{oc}$</th>
<th>$\Delta$</th>
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</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td>45° 1 52° 22°</td>
<td>24° 04</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>45° 1 50 28</td>
<td>17° 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>45° 1 48 37</td>
<td>8° 54</td>
<td></td>
<td></td>
</tr>
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<td>0.1</td>
<td>0.1</td>
<td>45° 1 10 08</td>
<td>5° 00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>45° 0.5 39 56</td>
<td>12° 53</td>
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<td></td>
</tr>
<tr>
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<td>0.1</td>
<td>0.1</td>
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<td>29° 07</td>
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<td></td>
</tr>
<tr>
<td>0.3</td>
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<td>0.1</td>
<td>45° 0.5 30 53</td>
<td>9° 43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>45° 0.5 44 48</td>
<td>3° 16</td>
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<td></td>
</tr>
<tr>
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<td>0.1</td>
<td>45° 0.5 45 46</td>
<td>1° 00</td>
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<td></td>
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<tr>
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<td>0.1</td>
<td>0.1</td>
<td>45° 0.5 44 41</td>
<td>4° 12</td>
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<tr>
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<td>0.1</td>
<td>45° 0.5 40 41</td>
<td>13° 42</td>
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<td></td>
</tr>
<tr>
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<td>0.1</td>
<td>45° 0.5 44 46</td>
<td>1° 41</td>
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<td>0.1</td>
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<tr>
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<td>0.1</td>
<td>0.1</td>
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<td>0.1</td>
<td>45° 0.5 32 53</td>
<td>13° 42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

However, even in these cases the errors of the AM method lie between $20^\circ$ and $30^\circ$, which is an acceptable result at least for statistical purposes. Furthermore, we have to notice that the ecliptic longitude of the computed pole is in general more reliable than the ecliptic latitude, the error of $\lambda_{oc}$ being about half of the error of $\beta_{oc}$.

Figs. 2 and 3 show the results obtained for two extreme cases among those listed in Table I. The figures present the lightcurves corresponding to the four values of the chosen longitudes, a view of the object at minimum and at 90° aspect, the A-V(MAX) plot with the
1. \( \text{ASP} = 90^\circ, \text{AMP} = 0.39 \) \( V_0 = 0.75 \)
2. \( \text{ASP} = 106^\circ, \text{AMP} = 0.29 \) \( V_0 = 0.72 \)
3. \( \text{ASP} = 118^\circ, \text{AMP} = 0.18 \) \( V_0 = 0.65 \)
4. \( \text{ASP} = 123^\circ, \text{AMP} = 0.14 \) \( V_0 = 0.62 \)

\[ A_1 = 0.50, A_2 = 1.50 \]
\[ B_1 = 0.70, B_2 = 0.70 \]
\[ C_1 = 0.50, C_2 = 0.50 \]

PHASE = 0, OBL. = 0, NO SCATTERING

\[ \frac{A}{B} = 1.43, \frac{B}{C} = 1.29 \]
POLE = \( (\theta, \phi) = (8, 37^\circ) \)
\( \Delta = 0.5^\circ \)

\[ A_1 = 0.10, A_2 = 1.30 \]
\[ B_1 = 0.70, B_2 = 0.70 \]
\[ C_1 = 0.05, C_2 = 0.95 \]

PHASE = 0, OBL. = 0, NO SCATTERING

POLE NOT FOUND
"observed" points and the best-fit curve (see later).

For what concerns the cases for which no solution was found, we have to notice that they refer to simulations where the b/c ratio could not be computed by means of the A-V(MAX) relationship. In fact, for a triaxial ellipsoid with a given a/b ratio, the A-V(MAX) relationship is function of the b/c ratio and belongs to a family of curves, some of which are shown in Fig.4. In our computations the "observed" lightcurve amplitudes and V(MAX) are fitted by a curve of this family computed by means of least-squares. However, in some cases, it is not possible to find any curve corresponding to plausible values of b/c ratio, as, for instance, reported in Fig.3, where the trend of the points is evidently not compatible with any curve of the expected kind. This happens mostly when the shapes of the models largely differ from regular ones. We would like to stress that in the case of real observations the trend of the A-V(MAX) relationship is decisive for inferring significant deviations from the triaxial shape and, consequently, for the application of methods like the AM. On the other hand, when it is possible to fit the observed amplitudes and magnitudes by means of a "regular" curve (in the sense of Fig.4), we can be very confident that the shape is almost triaxial and the pole determination is quite accurate.

We have to notice that the pole solutions found by least-squares have, in general, mean quadratic errors much smaller than the corresponding $\Delta$. This is probably due to the fact that with the fixed parameters a moderate range of aspects (and consequently of amplitudes) is available. It follows that the reliability of the b/c solution could be quite low. However, in real cases the possibility to cover a wide range of aspects is not only due to observational problems, but to the actual position of the pole itself. In fact, for a quasi ecliptic orbit and for rotation axes close to the ecliptic pole, the range of possible aspects decreases sensibly, implying less accurate values of the computed poles. This fact evidences the necessity to enlarge the present preliminary analysis to different pole positions, in order to create an "error map" on the whole celestial sphere.

As a conclusion of this preliminary study, we think that realistic errors in the asteroid pole determinations could be even less than 10° in favourable cases, i.e., when we consider objects for which reliable photometric data exist, and the lightcurve morphology and the trend of the A-V(MAX) curve are in agreement with a triaxial ellipsoid shape. In less favourable cases, the reliability of the solutions is lower, but the presence of significant deviations from a regular triaxial ellipsoid shape should be "a priori" expected both from the lightcurve morphology, and mainly from the A-V(MAX) trend. However, we cannot reach definitive conclusions at this stage; a larger number of simulations are needed in order to study the behaviour of the solutions when different "true" pole positions are considered, different laws of scattering and large phase observations are taken into account, etc. More complex simulations are planned for the near future, and the corresponding results will be published in forthcoming papers.

REFERENCES


DISCUSSION

Knežević: Do you have some recipe to distinguish between various shapes that all fit the same observed lightcurve?
Cellino: For the moment, we can only say whether or not a given object differs significantly from a regular triaxial ellipsoid. The exact shape cannot be derived easily.
Meteors showers and Apollo asteroids (for example, METEOROID STREAMS ASSOCIATED WITH APOLLO ASTEROIDS: EVIDENCE FROM THE ADELAIDE RADAR) have been many suggestions of possible associations between disruptive streams by planetary close encounters and non-shower or sporadic meteors originating in the orbit of the comet in question. These streams are meteoroid streams which follow the heliocentric orbit of the comet in question. Although there had previously been several streams associated with different asteroids (in particular Adonis, Apollo, Hermes and Oljato) has been suggested but not proven. Here the 3759 meteor orbits determined at Adelaide in the 1960's have been compared to the orbits of all known Aten-Apollo-Amor asteroids using a new and powerful search technique. Strong evidence is found for streams associated with Apollo-type asteroids Icarus, Hermes, Adonis, Oljato, Hephaestus, 5025 P-L, 1982 TA, and 1984 KB; the final five in this list may be members of the Taurid-Artemis complex, as is Comet P/Encke. No stream associated with 1862 Apollo was identified, but this may be due to the lack of observations at the appropriate solar longitude. No streams associated with any Aten or Amor asteroid were found: this may be due to the limited detectability of their meteors, if they exist, because of their low geocentric velocities. In general streams were discovered for all asteroids coming within 0.1 AU of the Earth, having radiants observable from Adelaide and atmospheric velocities above about 22 km/sec: this suggests that meteoroid streams are a general feature of Earth-approaching asteroids.

1. Introduction
The dynamical lifetimes of Aten-Apollo-Amor (hereafter AAA) and Mars-crossing asteroids are of the order of 10-20 years: this is much shorter than the age of the solar system so that a replenishing source is required (e.g. Rickman, 1985). Opik (1963) suggested that these asteroids are at least in part the moribund cores of defunct comets which no longer show obvious comet-like activity. Although a mechanism whereby such bodies could be dynamically perturbed from the asteroid belt into planet-crossing orbits has now been found (Wisdom, 1983; Wetherill, 1985) there are still reasons to believe that an interlinkage exists. Despite the fact that there are general dynamical differences between comets and asteroids (Whipple, 1954; Kresák, 1984), there are asteroids in comet-like orbits (Hahn and Rickman, 1985) and equally well P/Encke could be said to be on an asteroid-like orbit. In addition, physical studies of comets and AAA's have shown a lack of clear distinction in many cases (Davies, 1986; Hartmann et al., 1987): particular examples are 2201 Oljato (McFadden et al., 1984, 1985; Russell et al., 1984), and 2101 Adonis (Ostro, 1985). Thus, the differentiation between asteroids and comets which has historically been based upon telescopic appearance has become blurred and much similarity is now recognized.

Another feature often associated with comets, at least those which approach the Earth to within about 0.1 AU, is the existence of meteor showers and hence meteoroid streams which follow the heliocentric orbit of the comet in question. These streams are formed from the larger dust particles ejected by the comet each time it passes perihelion. The association of such showers with comets has been well-known for over a century (e.g. Porter, 1952; Drummond, 1981) and generally comets have been regarded as being the major source of meteoroids, with non-shower or sporadic meteors originating in the disruption of streams by planetary close encounters (Olsson-Steel, 1986). Although there had previously been many suggestions of possible associations between meteor showers and Apollo asteroids (for example, Hoffmeister, 1948; Sekanina, 1973, 1976; Drummond, 1981; Balamadzhanov and Obrubov, 1983), the first incontrovertible link between an asteroid and a shower was found in 1983 when the Geminid parent, asteroid 3200 Phaethon, was discovered by the IRAS (Davies, 1986). There is therefore renewed interest in looking for meteor activity linked with AAA asteroids, and this paper describes a search for such links amongst the radar meteor orbits determined from Adelaide, South Australia, in the 1960's. A new and powerful search technique is used, which for the first time allows a stream to be recognized when it has similar orbital characteristics as the sporadic background. It is shown that there are several cases of Apollo-type asteroids possessing meteoroid streams and that for all other Apollos the absence of a detected stream may be explained by the fact that they do not pass sufficiently close to the Earth for stream-intercept to occur, their geocentric velocities (and hence meteor ionizing efficiencies) are too low, the radiants are too far north to be detected from Adelaide, or no data were collected near to the times when the radiant might be active.

2. The Adelaide Data
Two radar meteor orbit surveys have been conducted by the University of Adelaide (35°S), and these are the only surveys yet conducted from the southern hemisphere although a new program is now commencing in New Zealand (Steel and Baggaley, 1985). The first Adelaide survey ran from 1960 December to 1961 December and resulted in 2092 individual orbits to limiting magnitude +6 (Nilsson, 1964). Generally observations were made for about one week every month, although there was a special campaign straddling July/August since in the southern hemisphere the greatest meteor activity is seen at that time of year (Keay and Ellyett, 1969). The second Adelaide survey was conducted at the end of that decade, and meteor to limiting magnitude +8 were detected. A total of 1667 orbits of meteors observed in 1968 December and 1969 January, February, March, June and October were computed and the results published by Gartrell and Elford (1975). Again the observation periods only ran for up to a week in each month, so that short showers occurring in the other three weeks of each month, or in the other six months of the year in the case of the later survey, would not have been detected. In addition, due to the southerly observation site few meteors...
with radiants north of 30°N were observed. Thus there are many showers, and theoretical radiants of parent asteroids, which could have not been detected by these surveys.

Further details of the Adelaide radar meteor orbit surveys, including radiant and orbital element distributions, have been given by Olsson-Steel (1987a). The individual orbits are now archived at the IAU Meteor Data Center at the Lund Observatory, Sweden.

3. The Stream-Search Technique

When inspecting large data sets such as those produced by radar meteor orbit surveys for patterns which might indicate the existence of a meteoroid stream, account must be taken of the distribution of each of the orbital elements in the data set; the search is made especially difficult since not only is there 'noise' in the form of sporadic orbits (the 'signal' being the stream orbits), but also the individual orbits are 'noisy' in that the precision of the radar measurement techniques means that the individual elements are not well-determined. If a stream has one or more elements which are distinct from the majority of the sporadics then the recognition of the stream is relatively straightforward: a preponderance of orbits with measured elements \( \dot{\varepsilon} = 160° \pm 10° \) and \( q = 0.5 - 0.7 \) AU occurs only in May and October each year, and these are the Halley showers; similarly orbits of large semi-major axis \( a = 1.5 - 3 \) AU and \( i = 25° - 40° \) occur only in December and these are from the Mono-cerotid stream.

However the bulk of the orbits in any survey do not have any such unique characteristics: they are mainly of low inclination \( (\dot{\varepsilon} < 20°) \), semi-random perihelion distance \( (q) \), small semi-major axis \( (1.5 < a < 3 \) AU), moderate to large eccentricity \( (0.5 < e < 1) \), and semi-major axis \( (a) \), helion \( (\omega) \): for example see the orbital distributions plotted by Olsson-Steel (1987a), or for the Harvard surveys by Sekanina (1973, 1976). Any search based upon a single orbital element, or using the multi-element orbital discriminants of Southworth and Hawkins (1963) or Drummond (1981), may find a large number of meteor orbits which appear similar to the orbit of a particular short-period comet or AAA asteroid, but this may be due to a concentration of sporadic orbits of similar gross characteristics.

Thus the more fact that a test orbit is similar to a large number of meteor orbits may be misleading: for example, on the basis of the D-criterion of Southworth and Hawkins (1963) Comet 1770 I Lexell has more correlated meteor orbits in the Adelaide data than any other comet, but nevertheless it is doubtful whether any stream is genetically associated with it (Kresˇkáková, 1980; Olsson-Steel, 197b).

The new stream-search technique used here overcomes these drawbacks, as follows. For either D-criterion (Southworth and Hawkins, or Drummond),

\[
D = \text{function} \left( q_{0}, e_{0}, \dot{\varepsilon}_{0}, i_{0}, \omega_{0}, a_{0}, q_{j}, e_{j}, \dot{\varepsilon}_{j}, i_{j}, \omega_{j}, a_{j} \right) \]

where the subscript '0' denotes the test object (the asteroid or comet) and the 'j' denotes a particular meteor orbit (i.e. \( j = 1 \) to 3759 for the Adelaide data). Now, assuming that the Earth's orbit to be circular, the closest approach distance by the asteroid or comet is:

\[
d_{0} = \text{function} \left( q_{0}, e_{0}, \dot{\varepsilon}_{0}, i_{0}, \omega_{0}, a_{0}, q_{j}, e_{j}, \dot{\varepsilon}_{j}, i_{j}, \omega_{j}, a_{j} \right) = \text{function} (\varepsilon_{j})\]

and \( d_{0} = 0 \) for the meteor else it would not have been observed. Since \( d_{0} \) does not depend upon the longitude of the ascending node \( \Omega _{0} \), if the data set were made up entirely of random sporadic orbits then for any particular \( (q_{0}, e_{0}, \dot{\varepsilon}_{0}, i_{0}, \omega_{0}, a_{0}) \) the number of correlated orbits on the basis of either \( D \) would be approximately constant, and hence independent of \( \Omega _{0} \); thus by entering any value for the nodal longitude \( \Omega \), always about the same number of 'correlated' meteor orbits would be found.

However, if in reality the data set is non-random and streams exist, then a larger number of correlated orbits would be expected near to \( \Omega = \Omega_{0} \) than at any other value of \( \Omega \). For example, if \( (q_{0}, e_{0}, \dot{\varepsilon}_{0}, i_{0}, \omega_{0}, a_{0}) \) were the real values for 3200 Phaethon, then many more correlated meteors are found at \( \Omega = 240° \) \( 290° \) and \( \Omega (\text{Phaethon}) = 265° \) (cf. Figure 1). There are many fewer similar meteor orbits at all other values of \( \Omega \); these are part of the sporadic background, the peak being due to the Geminid shower of which Phaethon is the parent. The plot for this asteroid might be considered a result of some drawback from this new form of analysis, since it results from a strong and distinct stream originating from a parent with orbital characteristics almost identical to those of the well-studied stream. A similar (but perhaps noisier) form would be expected for other objects which are the parents of substantial numbers of meteors detected in the Adelaide surveys.

4. The Aten-Apollo-Amor Asteroids

As expected, several of the comets known to be meteor-producers show evidence of streams in the Adelaide data. However the strongest showers, judging from the numbers of correlated meteors which are found, appear to be related to the Aten, Apollo and Amor asteroids; in particular the largest number of associated meteors is found for Jupiter-crossing body 5025 P-L, and this asteroid along with 2201 Oljato, 2212 Hephaistos, 1982 TA and 1984 KB may be part of the Taurid-Arietid complex (Bailey et al., 1986; Olsson-Steel, 1987a). No streams were found for any of the Amor asteroids, and this could be due to their low geocentric velocities at aphelion and perihelion respectively, this limiting the meteor detectability; also for a shower originating from an Amor to be detectable the stream would have to be quite diffuse at perihelion so as to allow some meteoroids to be Earth-crossing, and this would hinder the recognition of a coherent stream.

Considering now only the Apollo asteroids, the following process (as outlined in section 3) was carried out. All Apollos through to the end of 1987 June (i.e. up to and including the re-discovery of 1959 LM = 1987 MB) were studied, and for each the parameters \( (q_{0}, e_{0}, \dot{\varepsilon}_{0}, i_{0}, \omega_{0}) \) were used, along with values of \( \Omega \) running from 0° to 360° in 5° steps; at each longitude \( \Omega \) the values of \( D \) (Southworth and Hawkins and Olsson-Steel) were calculated using each of the 3759 meteor orbits: thus a total of 49 x 72 x 3759 x 2 = 26 million orbital comparisons were necessary. A meteor was judged to be associated with the test orbit if \( D \) was 0.20 and/or \( D' \) was 0.125. Several of these Apollos do not pass near by the Earth so that even if the asteroid did possess a meteoroid stream it would not have been detected.

Of the 49 Apollos, 11 have at least \( N \geq 10 \) associated meteor orbits on the basis of \( D \) and/or \( D' \) at the 'real' value of the nodal longitude, \( \Omega = \Omega_{0} \). These are all shown in Fig. 1, along with which has often in the past been suggested as a shower parent and also 1986 JK (another possible meteor progenitor: Drummond, 1986). In each case \( N \) is plotted against \( \Omega \) and the value of \( \Omega_{0} \) is indicated. Recalling the comments in section 3 concerning the archetypical plot for 3200 Phaethon and its strong, well-known meteor stream (the Geminids) it is immediately apparent that 5025 P-L, 1984 KB and 1956 icarus possess streams, as shown by the strong peak in \( N \) very close to \( \Omega = \Omega_{0} \); this has often in the past been suggested as a shower parent (see the past (Sekanina, 1973, 1976). Additional work 1982 TA 2201 Oljato and 1937 UB (Hermes) also show the characteristic form expected for an associated stream, although with the peak in \( N \) offset slightly from \( \Omega_{0} \).
Figure 1. The number of correlated Adelaide meteor orbits for various Apollo asteroids. The real orbital parameters of each asteroid were used, except that the longitude of the ascending node was varied from 0° to 360° to find out whether there is a concentration of meteor orbits with \((q, e, i, w)\) similar to the elements of the asteroid at a particular nodal longitude \(\Omega\). The vertical line terminated by crosses shows the real value of \(\Omega\) for each asteroid.
5. Do all Apollo asteroids have meteoroid streams?

Having discussed above and shown in Fig. 1 those asteroids which appear to have meteoroid streams for which there is evidence in the Adelaide data, it is necessary to examine those asteroids for which evidence is not found. As previously mentioned, no Amor or Aten asteroids rendered detectable showers in these data, and this may in part be due to their low geocentric velocities: the ionizing efficiency is a strong function of the velocity. A similar comment applies to the Apollo asteroids: if they have low geocentric velocities then their meteoroids will have low radar-detection probabilities. Denoting the velocity at the top of the atmosphere (i.e. after acceleration by the Earth's gravitational field) by $V_o$, the asteroids in Fig. 1 which do seem to have streams have velocities ranging from $V_o = 35$ km/sec for Phaethon down to $V_o = 22$ km/sec for Hermes, whereas the final four (1982 Apollo, 1959 LM, 1983 LC and 1986 JK) all have $V_o < 21$ km/sec: this suggests that the low values of $V_o$ may have hindered the detection of such streams as may exist. In fact of the original 49 Apollos studied here, 33 come within 0.1 AU of the Earth but do not have streams recognized in the present analysis. Of these 33, 22 have $V_o < 21$ km/sec, and a further 3 have $21 < V_o < 22$ km/sec. Of the remaining 8 Apollos from the 33, the absence of detected streams can be explained either by the theoretical radiant being too far north, or else the absence of data collection at the longitude of closest approach by the asteroid (cf. section 2, and Olsson-Steel, 1987b). Finally, the absence of streams can be explained by the theoretical radiant being too far south, or else the absence of data collection at the edge of the stream rather than the core centered on the parent. An alternative explanation, which might also apply to 2101 Adonis and 2212 nepheloid for which the peak in N is well-separated from $\alpha_o$, is that the stream meteoroids have orbits which have shrunk slightly under the Poynting-Robertson effect and therefore suffer differential secular perturbations compared to the parent asteroid on a larger orbit (Babadzhanov and Obrubov, 1984). The final four Apollos (1862 Apollo, 1959 LM, 1983 LC and 1986 JK) show no evidence of streams, and have elevated values of $\delta$ (i.e. high 'noise') since each of the four has $\delta < 6^\circ$: such a low inclination is typical for the sporadic background meteors.

The above discussion may be summarized as follows (see Olsson-Steel, 1987a for more details):

- Clear evidence is found here for meteoroid streams associated with each of the Apollo asteroids for which the data collection times and techniques were favourable.

In other words, it appears that:

Meteoroid streams may be a general feature associated with Apollo asteroids.

These streams may be evidence that the Apollos are currently inactive or exhausted cometary nuclei; alternatively the meteoroids may be collisional debris lost by the asteroids in the present stage of their evolution. Clearly there is much scientific import still to be gained from the various meteor orbit surveys conducted over the past few decades, and a re-analysis of the available data using the new method described here should yield extremely significant results.

Acknowledgements

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Babadzhanov: Your conclusion on the meteoroid streams and Apollo asteroids is correct if meteoroids were ejected recently. But meteoroids were ejected too long ago and we cannot compare meteoroid streams and Apollo asteroids according to the D-criterion and similarity of their orbits because these orbits differ significantly. So when comparing the orbits of meteor streams and Apollo asteroids it is necessary to take into account variations of orbital elements as influenced by planetary perturbations.

Olsson-Steel: The above comment is entirely correct and this constraint implies that these streams were formed within the past $10^3 - 10^4$ years. It would be interesting to see what the time-scale is for collisions by boulders onto Apollo asteroids, and hence the possible production of such streams if they were not formed when the "asteroids" were "comets". So these results imply either that Apollo asteroids are often struck by large objects ($\sim 10^4$ m), or else they are the result of a recent enhancement in the number of comets.

Farinella: If confirmed, the result that all or most Apollos are associated with meteor streams is very interesting. Instead of the usual "dead comet" interpretation, this could mean that meteors are collisional ejecta from real (rocky) asteroids. The relevant impacts had to occur recently enough (say, $\sim 10^4$ yr ago) to avoid strong changes of the orbital elements due to planetary perturbations. Do you agree?

Olsson-Steel: This is a very useful and interesting question which encompasses also the comment of P.B. Babadzhanov. I agree with your comment, and the time scale you mention is appropriate not only for planetary perturbations, but also the time-scale for the loss of 1 mm meteoroids in Apollo-type orbits due to catastrophic collisions with zodiacal dust is ($\sim 10^5 - 10^6$ years) which puts an additional time-constraint onto the scene.

School: You said, you observe meteor streams associated with asteroids. Are you sure that what you observe are complete streams? Is it possible that these are fragments of streams what you observe?

Olsson-Steel: Many of these asteroids appear to be the parents of recurrent annual streams (1566 Icarus and the Daytime Zeta Arietids; 3200 Phaethon and the Geminids 1982 TA, 1984 KB, 5025 P-L and the Taurid-Arietid complex, the parent of which has been assumed to be comet Encke; 2201 Oljato and the Chi Orionids, which is also part of that complex). Thus, it appears that the streams are complete loops rather than arcs. The time-scale for loop-formation (due to radiation pressure and ejection velocities) is only $\sim 10^3$ years.

Napier: On the question of asteroidal (in a main-belt sense) versus cometary origins for the Apollo asteroids examined: quite a few of the bodies are part of the Taurid-Arietid system, which has Encke's comet as a member. If we are to think of a common origin for these bodies, then presumably they are inactive comets.

Olsson-Steel: Yes: possibly these asteroids were once part of a larger body which included Encke, or perhaps they represent separate bodies which are in some other way genetically related. The existence of one asteroid (5025 P-L) in a Jupiter-crossing orbits suggests that they (including Encke) were all part of a super-comet which was fractured in a close approach to Jupiter, with the bodies which did not quickly attain a small aphelion distance (Q<4.5 AU) having been rapidly ejected: 5025 P-L is then one body which has so far managed to evade ejection. The ejection time-scales suggest that this occurred $\sim 10^4 - 10^5$ years ago.

Kresak: The orbit of 5025 P-L is very poorly determined. If you take into account its uncertainty, how sure you are that the stream you have identified is associated with this asteroids, and not with P/Encke?

Olsson-Steel: You are correct that the orbit is not well determined; however it is better known than the meteor orbits used here, so the inaccuracy I largely discount. It is important to note that I do not suggest that 5025 P-L (or 1982 TA, or 1984 KB) are the parents of the complex rather than P/Encke: I suggest here that they all appear to be related to the meteoroid complex and to each other, and it seems likely that they were all at one time part of a single, much larger, body. Other objects derived from this body may be the Tunguska object and the Brno fireball. A long-period comet (1967 II Rudnicki) may also be related.
PRESENT STATUS OF PHOTOMETRIC PARAMETERS OF ASTEROIDS

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DK - 8000 Aarhus C, Denmark

ABSTRACT. The external accuracy of photometric parameters of asteroids is investigated by comparison of published lists. Absolute magnitudes are consistent at the +0.1 mag level but phase coefficients are still rather uncertain.

1. Introduction

Intercomparisons between different catalogues are the standard procedure for estimating their random and systematic errors. For consistent data an investigation of the systematic differences between independent series of observations may result in improved accuracy by a combination of the data to a mean system. This level of development and refinement has for a long time been reached by catalogues of star positions, magnitudes, parallaxes and so forth. Our aim is to take a first step in this direction for photometric data of asteroids, if possible at all.

The great difficulties in obtaining reliable photometric data for asteroids are well known. A main problem is that a great number of observations are needed in order to eliminate lightcurve and aspect variations; if not eliminated, the observations will be degraded by a large, random-like component. Another difficulty is due to the dependence of brightness on the solar phase angle /$\beta$/. The phase curves are assumed to depend on a single shape parameter determined by the surface texture. An additive constant, the absolute magnitude, depends on albedo and diameter. At present, the shape of the phase curves has to be determined empirically, and this raises two problems: sets of accurate standard phase curves must be determined and there is an inherent indeterminateness in the definition of the shape parameter because any monotoneous function of this may be used as shape parameter as well. In practice, the first difficulty reduces the weight of observations at small phase and the second difficulty gives an arbitrariness in the scale and zero point of the shape parameters.

2. The data compared

Three recent lists, here denoted by roman numerals I, II and III, have been compared. The first list I is an improvement by Gehrels and Tedesco /1979/ of a long-term I.A.U. standard. This list states the classical phase coefficients, the definition of which takes advantage of the approximate linearity of phase curves in the range $6^\circ < \beta < 20^\circ$. The straight line is specified simply by its coefficient and zero phase value. Apart from convenience in practice and familiarity by long-term use, this classical definition has the advantage that zero points and scales are fixed within small limits. Table 1 gives the asteroid number and $V'$ as the stated $B'/1.0/ corrected by the color index $B-V'$, as given by Bowell et al. /1979/. The phase coefficients $/V'$ are given in units of .001 mag/deg. The mean values of the phase angles of the observations are not reproduced because these essential data are lacking in the comparison data.

The second listing is essentially due to E. Tedesco /1986/ and complete for all numbered planets. The photometric parameters stated are $H$ and $G$, defined in I.A.U. Transactions 19 B/1985/, 184. For 237 objects or about 7% of the total, $G$ is based on a real determination but heretofore are mainly interested in the subset of 78 objects, which are present in the two other lists. The distribution of $G$ for 237 objects is nearly uniform in the interval $0< G < 0.35$ but a peculiar discontinuity at $6^\circ$ may indicate an artificial cut-off.

The third list by Lagerkvist and Williams /1987/ is based on a well-documented and homogeneous observational material over large phase intervals. Different oppositions with varying aspects are not combined and we may expect the phase coefficient to be well determined. In 14% of the cases $G$ is negative. The adopted standard phase functions fitted to the observations are clearly stated.

For the comparison it is convenient that the quantities are approximately equal or at least similar. Phase functions are therefore specified by $V'$ and $V''$, as defined in Kristensen /1987/. The approximate numerical relation for the phase functions used by Lagerkvist et al. is:

\[
V = H + 0.31 - 0.276
\]

\[
\Phi = \frac{-0.234 + 0.0687(G + 1.00)}{1/2}
\]

Similar relations are valid for the phase functions adopted officially by I.A.U. Comm. 20. The deviations, mainly in $V'$, are small and the transformations above may be used in all cases.

3. Discussion

Data I and II are consistent and especially higher numbered objects are basically identical /for instance nos. 20, 32, 51, 77, 78, 88, 89, ..../ . However, the data base may partly be the same with a few improvements /for instance 129/. In case II and III the data are independent and the absolute magnitudes $/V'$ give the root mean square difference .15 mag. Unless the quality of the two lists is very different, this suggests that their mean errors are of order .001 mag in $V'$. In some cases /9, 29, 324, 451, 479, ..../ differences exist at the
4. Lagerkvist C.l and Williams J.P.: Deter-
mination of slope parameters and absolute magnitudes for 51 asteroids.


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Figure 1.
Phase coefficients by Lagerkvist et al. (III) plotted against the M.P.C. standard (II). Dots mark points with the smallest expected accuracy (large lightcurve amplitudes, small phase interval, few observations or G values not determined by direct use of photometric data). Higher and higher accuracies are marked by x and o. Even the best data indicate no correlation.
UNUSUAL MOTION OF AMOR

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Precise analysis of the orbit of minor planet (1221) Amor, based on all observations made in 1932-1980, shows that in 1956 there was an unexplained event in the motion of the asteroid. Possible interpretations of that fact as well as peculiarities in the long-term motion of Amor in 1650-2170 are discussed. The ephemeris of Amor for 1988 is presented.

1. Introduction

The minor planet (1221) Amor belongs to a group of objects which make relatively close approaches to the Earth but do not overlap the Earth's orbit. Together with Apollo and Aten groups they constitute a class of the so-called Earth-crossing asteroids, which are interesting due to their origin. For example, many of them appear to be extinct comet nuclei.

Amor was discovered in 1932 by E. Delporte in Uccle when the minor planet approached the Earth to within 0.108 AU. Its orbital period was found to be close to 8/3 years. It means that after the time interval of 8 years in which Amor makes 3 revolutions round the Sun, a close approach of the asteroid to the Earth should be repeated. This fact gave a chance to observe the object, which is one of the smallest among known Earth-crossers, every 8 years.

Up to now Amor was observed in 7 oppositions from 1932 till 1980 (although Schubart (1969) published ephemerides of Amor for pre-discovery approaches in 1924 and 1916, no earlier observations were found unfortunately). The observational material obtained during those apparitions is characterized in Tab. 1. A total number of 279 observations were selected and weighted according to objective mathematical criteria (Bielicki 1972, Sitarski 1983) in the iterative process of differential orbit improvement applied to each opposition separately. The mean residuals thus obtained indicate the quality of suitable observational data. The weighted mean value of these residuals (amounting 1.49) may be used as a priori mean residual of the whole observational material. A comparison of the a priori value of the mean residual of observations made in some oppositions with the suitable value of the mean residual obtained as the result of orbit improvement based on the same set of observations and on a model of the asteroid motion can give us some information about quality of the adopted model. When the mean residual computed from the model of motion is closer to the appropriate a priori value, we can consider that the model is better.

2. What happened in 1956?

Attempts to link all observations made in 1932-1980 by one system of orbital elements showed that the motion of Amor is perturbed not only by n-•• planets but also by some unknown forces. These effects are very small and it is easy to miss them during the orbital computations. While Schubart (1969) reported a special subterfuge enabling to link 5 apparitions in 1932-1964, Landgraf (1984) announced a successful determination of the Amor's orbit from 261 observations made in 7 oppositions.

However, precise and deep analysis of the course of residuals shows that in 1956 the motion of Amor was disturbed by unknown factor. Namely it appears that a set of 43 observations made in this opposition can be distinctly divided into two parts:

II. 24 observations from the period of Feb 15 - Mar 20,
II. 19 observations from the period of Apr 2 - Jun 5.

It is worth pointing out that on March 21 Amor passed the Earth at the minimal distance of 0.115 AU, and that its perihelion passage occurs on April 3.

The mean residuals of unit weight of observations in part I and part II amount to 0.74 and 1.65, respectively, and they are drastically less than the mean residual of the whole set of 1956 observations (see Tab. 1). This fact can serve as the first proof that such a division is not random and has a physical sense. The second one may be the diversity of orbits obtained separately from the observations of parts I and II. It appears that the orbit based on the observations from part I represents the observations from part II with the mean residual equal 26.18 and vice versa, the orbit based on the observations from part II represents the observations from part I with the mean residual equal 5.97. It is necessary to point out that the analogical test, for example in the case of 1964 apparition...
of Amor, shows that the suitable values of mean residuals amount to 4.75 and 2.96, respectively. 

There is another fact confirming the unknown events in the motion of Amor not only in 1956 but also during its unobserved revolutions between 1948 and 1964. Successful (in a sense explained in the end of Introduction) linkages of observations made in 1932-1956 and in 1956-1980 just as in 1948-1964 turned out to be impossible. Similarly, the attempts to link the observations made in 1932, 1940, 1948 and in part I of 1956 as well as in part II of 1956, 1964, 1972 and 1980 gave unsatisfactory results. For example, in the case of the period from 1932 till 1956 (part I) the a priori mean residual amounts to 1.34, while the mean residual obtained in the process of orbit improvement based on all observations from that period amounts to 2.06. The really successful linkages were found only for the apparitions 1932-1948 (for example the suitable mean residuals are equal to 1.65 and 1.69, respectively) and 1964-1980.

All those facts can be considered as the proof that the motion of Amor was disturbed about 1956 by unknown factors. What can we say about their physical nature? First of all it is arousing suspicion that Amor, during its successive revolutions round the Sun, passed on the meteoroid stream a few times. As a consequence of probable collisions the orbit of Amor could be changed. From among the known streams one of the candidates may be the Lyrid meteor shower, for which the maximum of activity occurs in mid April. It appears that the minimal distance between orbits of Amor and Lyrids amounts to 0.04 AU.

The next possible interpretation of unknown disturbing forces in the motion of Amor about 1956 is connected with the conjecture that some Earth-crossing asteroids are extinct cometary nuclei. Assuming that Amor is a young death comet it is reasonable to suppose that the thin crust on the surface of Amor was suddenly split up and volatile constituents from the inside of the object were ejected. In consequence Amor could become again a very low active comet for a short time. Its activity was too small to be observed, but great enough to change the orbit. This conclusion may be supported by the detection of very small "nongravitational effects" in the motion of Amor in the period 1964-1980. It appears that the secular change of the semi-major axis of the Amor's orbit, which may be considered as a measure of the nongravitational anomaly (Sitarski 1983), computed from the observations made in 1964-1980, amounts to \((0.16 \pm 0.08) \cdot 10^{-10} \text{ AU/day}\) and reduces the mean residual from 1.63 to 1.30 (the suitable a priori mean residual amounts to 1.27). For a comparison, the same nongravitational effect, computed from the observations made in 1932-1948 amounts to \((-0.04 \pm 0.05) \cdot 10^{-10} \text{ AU/day}\) and does not change the mean residual which amounts to 1.69, as was mentioned above. The obtained value of the secular change of the semi-major axis of the Amor's orbit is at least two orders of magnitude smaller than typical values for short-period comets.

3. The long-term motion

Numerical integration of the equations of motion of Amor in a time span of over 500 years backward and forward from the observational interval shows an interesting periodicity in the 8-year cycle of visibility of the asteroid. Amor can be observed during its approaches to the Earth only. But, as we can see from Fig. 1, the minimal distances between Amor and the Earth change drastically with time. It is especially interesting that the forthcoming approach may be one of the last oppositions during which we shall be able to see this mysterious object.

4. Let us observe Amor

All curiosities discussed here connected with the motion of Amor show a great importance of its observations during the coming apparition in 1988. The ephemeris for this opposition is given in Tab. 2. The photographic brightness was computed according to the formula published by Schubart (1969).

We are waiting for new observations of Amor in order to improve the results we have obtained hitherto and reported in this paper.

Acknowledgments

The author would like to thank Prof. G. Sitarski for useful discussions and comments concerning the work on Amor.

The computations were made with the R-60 computer at the Warsaw University. The paper was supported by the Polish Academy of Sciences in CPBP 01.20.
### Table 2

Ephemeris of Amor for 1988

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</table>

### References

- Landgraf W., 1984, Minor Planet Circulars, No. 9021.
METEORS
One of the most significant originators of meteor physics in thirties, Prof. Dr. Johannes Hoppe passed away in Jena at the age of eighty, April 20, 1987. What we can say on meteor physics at this symposium is devoted to him the natural way: he was at the beginning of it all. In his eminent dissertation "Die physikalischen Vorgänge beim Eindringen meteorischer Körper in die Erd-atmosphäre", published in Astronomische Nachrichten 262 in 1937, pages 169 to 198, he set up the basic equations of meteor physics, referred to for many years as Hoppe's theory. After the first attempts to constitute a theory of fragmentation of meteoroids during the atmospheric flight in sixties, Hoppe's theory started to be called "the single-body theory". His equations (e.g. in Pecina's paper, this publication: drag equation and evaporation equation) became a classical part of what we know about the interaction of a single unbreakable meteoroid with the atmosphere. In his dissertation for the first time, Prof. Hoppe found the complete solution of the drag and ablation equations on assumption of isothermal atmosphere, expressing velocity and mass as function of height in terms of the exponential integrals (third and fourth equation in Pecina's paper "Meteor Physics"; this publication TS-2). Only recently, his solution was substantially enriched, when also the distance along the meteor trajectory was expressed in terms of exponential integrals as function of time or height and generalized to any dependence of atmospheric density on height (Pecina, Ceplecha 1983; 1984; Bull. Astron. Inst. Czechosl. 34, p. 102; 35, p. 120). I propose to call "the single body theory" of meteoroid interaction with the atmosphere in this most general form of solution, simply as "Hoppe's theory" again, in memory of the decisive contribution of Prof. Hoppe to the solution of this problem of meteor physics.

When the systematic photography of fireballs, the bigger and deep penetrating meteoroids with enough observed change in velocity, gave us relevant observational material, Hoppe's theory (the single-body theory) proved to be valid with high precision of few meters in distance for more than 50% of observed bodies: a success of his theory, which Prof. Hoppe was able to follow in his last years.

After two operations of his leg in 1982, he send me a letter announcing his intention to compute the Tunguska meteoroid trajectory again. His mood at that time can be best seen from the letter itself:

Dr. Zdenek Ceplecha
Lekatolovna akademie Vd
Astronomicky Ustav
let us observar meteorid

Zdeněk Ceplecha

Dear Dr. Ceplecha!

I thank you very much for your welcome paper, "Importance of Atmospheric Models for Interpretation of Photographic Fireball Data," of authors P. Pecina and Z. Ceplecha (986). The first operation (12.1.1982) was not successful, the wound (26.1.1982) was nearly better. I hope in a short time to go without bandaged legs.

The year 1982 was for me very uneventful. Perhaps 1983 will be better. If the man is beyond twenty-five, he is salvable — but: man proposes, God disposes. Will now recalculate the Tunguska Meteor will.

Not yet finished.

With the best wishes for you, your wife, and colleague P. Pecina.

Yours sincerely

Johannes Hoppe

The next generations of meteor physicists and all scientists relying on data derived from atmospheric trajectories of meteoroids will forever remember the work of Prof. Johannes Hoppe.

Zdeněk Ceplecha
EVOLUTION OF METEOROID STREAMS

P. B. Babadzhanov and Yu. V. Obrubov
Institute of Astrophysics, Dushanbe 734670, USSR

ABSTRACT. A meteoroid stream generally considered to be an elliptical ring of relatively small thickness. Such shape is attributable to meteoroid streams in an early stage of their evolution. Differences in planetary perturbations influencing the meteoroid particles ejected from the parent body from various points in its orbit at different velocities and time can result in a significant thickening of the stream. Our studies on the evolution of the short-period meteoroid streams have shown that these streams can produce several couples of showers active in different seasons of the year.

INTRODUCTION

Based upon the observed peculiarities of meteor showers one may distinguish the following stages of meteoroid stream evolution:

1. A compact cloud of meteoroids in the vicinity of a cometary nucleus. An example is the Draconid meteoroid stream which produced meteor storms in 1933 and 1946.

2. Meteoroids are distributed unevenly around the parent body orbit. In the vicinity of the parent body there is a compact cloud of particles, but around the whole orbit there is a less dense stream component. This has been seen to be the case of the Leonids.

3. Meteoroids are distributed almost evenly around the orbit, i.e. there have been practically no changes in the observed meteor rate from year to year. Nongravitational effects result in a meteoroid mass segregation. Under the gravitational and nongravitational perturbations the meteoroids fill out the volume of space defined by secular variations in orbital elements. This results in an activity of twin showers caused by the passage of the Earth through a stream before and after its perihelion as well as brings about the formation of the northern and southern branches of a shower (the Taurids, the Geminids, the Quadrantids).

4. Further, the dispersion of orbits of stream particles becomes considerable. The shower activity becomes diffuse and occupies a large area in the sky while the rate of visual meteors is extremely low. Such showers are usually called meteor associations.

5. At the last stage of evolution the structure of a stream suffers the influence of collisions of meteoroids with the sporadic particles as well as the prolonged influence of planetary perturbations and the Poynting-Robertson effect /P-R/.

It should be noted that all principal characteristics of meteor showers obtained from observations refer only to those stream meteoroids whose orbits cross the Earth's orbit, i.e. satisfying the following condition:

\[ a (1-e^2)/2 \leq e \cos \omega \]

where \( a \) is the semimajor axis, \( e \) is the eccentricity and \( \omega \) is the argument of perihelion. The selectivity of observations defined by the equation (1) does not provide any reliable data on the whole magnitude of dispersion of meteoroid stream orbits. On the other hand, if the observations confirm the existence of twin showers or the northern and southern branches of these showers we may conclude that there are meteoroids in the stream whose orbits do not cross the Earth's orbit. For example, the southern and northern Taurids have the arguments of perihelion equal to 113.2° and 292.3° respectively. The argument of perihelion of the twin shower of its southern branch /i.e. the Taurids/ is equal to 246°. Although there are orbits with arguments of perihelion from 113° to 246° and from 246° to 292°, however, it is impossible to obtain any observational data on them because of selectivity.

ESTIMATION OF THE METEOROID STREAM AGE

We assume different ways to estimate the age of each meteoroid stream using the results of observations. If a meteoroid stream is at the initial stage of evolution the stream age may be determined by the length of the arc occupied by meteoroids, assuming the increase velocity of the arc to be known. Determined by this method the age of Draconids is 3 yr and the Leonids age is 400 yr /Plavec 1957/.

The second way is based on the operation of the P-R effect. Estimating the stream age in such a manner we suppose that after the ejection from the parent body the meteoroids of different masses have the equal semimajor axes. Taking into consideration this assumption Jones /1978/ estimated the Geminid's age to be 4.7 thousand yr and Babadzhanov and Obrubov /1983, 1984/ considered this age to be from 3.6 to 19 millennia.

The third way is based on the determin-
narrow at aphelion and wide at perihelion. At the initial stage of its evolution the stream is very flat, narrow at perihelion and wide at aphelion. Kazantsev, Sherbaum 1981; Fox et al., 1983. When modelling the Geminid stream evolution, Fox et al. 1983/ have adopted the radius of a cometary nucleus to be 10 km. The maximum ejection velocity of small particles with radius of 0.1 cm and density of 0.8 g cm\(^{-3}\) was found to be 660 m s\(^{-1}\) and the semimajor axes of meteoroid orbits were in the range 1.12 AU to 1.77 AU. The ratio of the stream width in the plane of the orbit to its thickness, i.e., normal to the orbital plane, is 1:7:1. It would take the Earth less than two days to intersect such a stream while the radar meteor shower activity lasts more than six days.

Hunt et al. 1986/ have attempted to explain the formation of the Geminids as a result of the collision of the Phaethon with other interplanetary object. It is probable that their results are not in accordance with observations because the authors assumed the collision to have happened recently.

Here we have discussed the papers on the formation of the Geminid meteor stream. For other meteor streams the results of modelling are in the same. However, the observed structure at a shower /for example, the Geminids/ cannot be explained only by the differences of ejection velocities of meteoroids from a parent body and radiation pressure /Obrubov 1980J, Jones and Hawkes 1986/ because over the stream lifetime the planetary perturbation and the P-R effect would change strongly the structure of the stream.

**THE EFFECT OF PLANETARY AND NONGRAVITATIONAL PERTURBATIONS ON THE METEOROID STREAM EVOLUTION**

Planetary perturbations generally change all the orbital elements of meteoroids and do not depend on particle masses. When studying meteoroid stream evolution it was often assumed that the orbital elements of all the meteoroids change in the same manner as those of the mean stream orbit /Gabadzhanov, 1980/; Fox et al. 1983/. Such an approach causes the stream shape to be the initial dispersion of meteoroids' orbits not to change with time. However, planetary perturbations can considerably increase the dispersion of the orbital elements of meteoroids and, eventually, change the shape of the stream. The P-R effect reduces the semimajor axis and the eccentricity of the orbit in a secular manner. The lower the mass and density of particles the larger is the P-R effect which causes the segregation of the semiaxes of particles depending on their mass. Recently Olsson-Steel /1987/ has considered the influence of the Yarkovskij-Radzievskij /Ya-R// effect on the evolution of the Geminids /s=0.1 cm, p=1.06 g cm\(^{-3}\). He has found that if the meteoroids rotate at a very high velocity of 10\(^4\) s\(^{-1}\) then over 10000 yr the elements \(i, \omega, \Omega\) would change by \(\Delta i=+0.06\), \(\Delta \omega =+0.11\), \(\Delta \Omega =+0.126\) respectively. However, these changes do not account for the scatter in these elements which has been obtained from photographic data. Thus, according to Jacchia and Whipple /1961/ the rms scattering of photo-
graphic orbits of the Geminids is $\Delta a=0.9^\circ$, $\Delta a'=1.7^\circ$ and $\Delta \Omega=0.5^\circ$. Furthermore, the Ya-R effect in a secular scale requires a constancy in the direction of the meteoroid rotation /Radzievskij 1978/ that seems to be hardly probable over a time interval of more than 10$^6$ yr.

The influence of nongravitational effects is strongly dependent on the sizes and densities of meteoroids and as time passes these effects in the correlation of the orbital elements of meteoroids with their masses. The P-R effect provides the most considerable contribution to this process.

To explain the observed features of meteoroid streams we have used the Halphen-Govyachev method to calculate the first-order secular perturbations. This method allows us to follow the changes in the orbital elements of meteoroids independently of their position in the orbit over a long time-scale, i.e. allows us to distinguish general changes inherent in all the meteoroids in a given orbit.

In the present paper we shall proceed from the initial dispersion of the orbital elements, resulting from the ejection of particles at different velocities and from radiation pressure. Such an approach enables us to estimate how much the planetary perturbations can change the dispersion of the orbital elements of meteoroids, and hence, the stream shape. The main attention is focussed on the Geminid and Quadrantid meteoroid streams since we have the most available information about them. The characteristic features of the structure and evolution of short-period meteoroid streams are peculiar to these streams.

THE GEMINIDS

Let us assume the Geminids to be formed 20 millennia ago as a result of the decay of a cometary nucleus the remnant of which is the asteroid Phaethon. The results of calculations of secular perturbations of Phaethon's orbit are given in Table 1.

Table 1. Secular perturbations in the orbital elements of the asteroid Phaethon /a=1.271 AU/. T=0 corresponds to 1950.0

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<th>$\Omega$</th>
<th>$\epsilon$</th>
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<td>228.8</td>
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<td>201.7</td>
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<td>0.26</td>
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If we assume the radius of the cometary nucleus to be 10 km than the small particles released from the cometary nucleus will move in orbits with semimajor axes from 1 to 1.7 AU and eccentricities from 0.88 to 0.92.

Table 2 indicates secular variations of the Geminids' orbits with semimajor axes of 1 and 1.7 AU. Tables 1 and 2 show that secular variations of the orbits are satisfactorily described by the following integrals of motion:

$1 / c_1 = 1 - e^2 / \cos^2 i = \text{const.}$

$2 / c_2 = e^2 / 0.4 \sin^2 i \sin^2 \omega = \text{const.}$
To estimate the shape of the stream remnants \( a, e, \) of the orbit with \( a = 1 \) AU, \( C_e = 0.20 \), \( C \alpha \) we used cross-sections normal to the velocity and using relations to have the values from 0 to 360 total volume of space defined by relations.

The integral \( /3/ \) was found by Moiseev \( /1945/ \), and \( /4/ \) by Lidov \( /1961/ \).

The difference between the longitudes of perihelion in the Sun's and those of Phaethon averages 5°-10° over the period under review. Hence, we may assume that stream turns as single unit. This fact may be used to determine the shape of the stream which it could take due to planetary perturbations. For this purpose in a first approximation let us assume the longitudes of perihelion of orbits of all the meteoroids to be constant:

\[ /5/ \quad C_\alpha = \omega = \Omega + \omega = \text{const}. \]

As is seen from Tables 1 and 2 and Fig. 1 the larger the orbital semimajor axis of the meteoroid, the faster its orbit changes.

Due to the differences in the change rate of initial orbital elements, as time progresses, the particles will fill up the total volume of space defined by relations \( /3-5/ \), i.e. by secular perturbations. The stream shape, for example, may be determined in the following way. The values of \( C_e = 0.13 \) and \( C_\alpha = 0.29 \) correspond to the orbit with \( a = 1.7 \) AU. Assuming the argument of perihelion to have the values from 0° to 360° and using relations \( /3-5/ \) we shall derive the corresponding values of \( e, \iota, \Omega \). Many of these orbits will determine an "outer" with respect to the Sun/surface restricting the meteoroid stream. Using the same method for the orbit with \( a = 1 \) AU, \( C_e = 0.20 \), \( C_\alpha = 0.27 \) we shall obtain the inner restricting surface. To estimate the shape of the stream restricted by these surfaces, we have constructed cross-sections normal to the velocity vector of the orbit which has the same elements \( a, e, \iota \) as the Phaethon's orbit, but \( i \) is equal to 0. The shape of the Geminid meteoroid orbit was determined by these cross-sections is presented in Fig. 2. Such a shape differs greatly from traditional notions of meteoroid stream which were usually supposed to be like an elliptic ring of relatively small thickness. The characteristic feature of the shape of a stream generated from our model is its very large thickness equal to 1 AU at a distance of the Earth from the Sun /Babadzhanov, Obrubov, 1986/.

Ejections of particles from a parent body for a long time period cause the orbits with identical semimajor axes to have different arguments of perihelion. Moreover, planetary perturbations increase the dispersion of orbital elements also due to the scatter in positions of particles around the orbit /Jones 1985/. The results of Table 2 and Fig. 1 show that the difference in arguments of perihelion of orbits with \( a = 1 \) AU and \( a = 1.7 \) AU was 31° over 20000 yr after the stream formation. Hence, the volume of space defined by the initial dispersion of orbital elements and by relations \( /3-5/ \) could be thought to be almost filled out.

If we add the condition \( /1/ \) to relations \( /3-5/ \) then, using the known semimajor axis and constants \( C_e, C_\alpha, C_\iota \) we can determine the orbital elements of a particle crossing the Earth's orbit. These elements may be calculated by the following formulae:

\[ /6/ \quad \mu = m \cdot e^2 + k = 0 \]

\[ /7/ \quad \iota = \arccos \left( \frac{1}{e^2} \right) \]

\[ /8/ \quad \omega = \arcsin \left( \frac{0.4 \cdot e^2 - c_2}{e \cdot \sin \iota} \right) \]

\[ /9/ \quad \Omega = \frac{180 \omega}{\sigma} \]

\[ /10/ \quad C_\alpha = \omega - \Omega \]

where \( m = 2^{\mu} ; n = 2 (1 - e^2) + \alpha = 0.6 ; \) \( k = (\alpha - 1)^2 \cdot (1 - e^2) \).

If equation \( /6/ \) has one admissible solution, then it follows from the equation \( /9/ \) that the intersection of the given orbit with the Earth's orbit occurs at four values of

\[ T = 10^{-3} \quad e = 0.1 \quad \Omega = 0.1 \quad \omega = 0.1 \quad C_\alpha = 0.1 \quad C_\iota = 0.1 \quad C_e = 0.1 \]

\[ a = 1 \quad \text{AU} \]

\[ a = 1.7 \quad \text{AU} \]
and and Geminids, the Canis-Minorids, the Sextantids, and the Geminids to be associated with the Sextantids. The geocentric radiants and velocities of the observed showers, namely the Geminids, the Canis-Minorids, the Sextantids, and the Geminids, are given in Table 3. Observational data show that among these four showers at least three showers are active, namely the Geminids, the Canis-Minorids, and the Sextantids as well as the Geminids. The reason for this phenomena is in the fact that the shower maximum activity date has not been observed. This observational fact is correctly explained in a number of papers /Sabad-Kresakova 1974/. The values of the positions of the radiants are in agreement.

The stream thickness defined by the observed mean orbits of the Geminids and the Canis-Minorids is in a region of intersection of the Sextantids' orbits with the Earth's orbit. The model stream width along the Earth's orbit is approximately 0.12 AU. If it will take the Earth about seven days to pass through such a stream, the Earth's orbit is approximately 0.12 AU. It will take the Earth about seven days to pass through such a stream. The Geminids, the Canis-Minorids, and the Sextantids, the Canis-Minorids and the Sextantids, are in good agreement.

According to numerous investigations of the Geminid evolution the variation in longitude of the ascending node of the stream is about -1.6° over a hundred yr. On the other hand the regression of the shower maximum activity date has not been observed. This observational fact is correctly explained in a number of papers /Babadzhonov, Obrubov, 1982, 1983, 1984; Fox et al 1982; Jones, Hawkes 1986/. The reason for this phenomena is in the fact that the stream cross-section in the ecliptic plane is displaced along the Earth's orbit at a rate of variation of perihelion longitude. It may be concluded that the displacement of the Geminid activity dates will be defined by the turn of the whole stream. The velocity of such a turn is determined by an average and

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<td>256-263°</td>
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<td>δ</td>
<td>31-36</td>
<td>34</td>
<td>31-36</td>
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<tr>
<td>v</td>
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<th>Daytime Sextantids</th>
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<td>190-197°</td>
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<td>161-162°</td>
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</tbody>
</table>

Fig. 3. The dependence of eccentricity, inclination and radii-vectors to orbital nodes of Phaethon orbit on perihelion argument. R and R, radii-vectors to ascending and descending nodes. R = 1 AU correspond to intersection of the Phaethon's and Earth's orbits: 1 - Canis-Minorids, 2 - Sextantids, 3 - Canis-Minorids, 4 - Geminids.
variation rate of the longitude of perihelion. Since this velocity /for example, for the Quadrantid orbit at present/ is about -0.05° over 100 yr, i.e. very small, it is impossible to detect it from observations. Plavec /1950/ revealed a very fast variation in the radius-vector to the descending node at which the Geminids are observed. Recognizing from this fact, the conclusion that observations of the Geminids since 1862 have become possible due to the approach of the stream to the Earth's orbit, assuming a size of the stream along the radius-vector of the descending node to be equal to its width along the Earth's orbit, many authors /Plavec 1950; Babadzhanov and Obrubov 1980; Hughes et al. 1980; Fox et al. 1983/ drew a conclusion that the Geminid meteoroids could be observed on Earth during 200-300 yr. However, the models of the Geminid formation and evolution indicate the dimensions of the stream along the radius-vector to orbital nodes to exceed considerably the width of the stream along the Earth's orbit. Therefore, the visibility period for the Geminids may also exceed the values discussed above. Jones and Hawkes /1986/ showed that the stream evolution over 10 yr. According to their results the general visibility period of the shower is more than 1000 yr, and a central core could be observable. The streams mentioned above do not explain the observed stream width and they conclude that it is necessary to investigate the stream evolution over 10 yr.

The XI century observations of the 14 fireballs are obviously in favour of prolonged observations of the Geminids. Tapovici, Terentjeva 1668/; Fox and Williams /1985/ as well as Hunt et al. /1985/ concluded that the fireballs mentioned above could not belong to the Geminids. But as the authors assume a possibility of ejection of meteoroids from the Earth at the time of the fireballs just at the same time, namely in the XI century, their conclusions can not be considered final. In fact the ejection of bodies responsible for fireballs could occur thousands years ago. The orbital elements of the fireballs mentioned above were not changed significantly that their encounter with the Earth in the XI century may be thought probable.

Finishing a review of papers on the Geminid stream evolution let's note that our main interest in the dynamics of the Geminid stream is due to the fact that the radius of the caustic comet were chosen to some extent arbitrarily. Furthermore we have used a qualitative method to estimate the influence of planetary perturbations. The smaller initial dispersion of meteoroid stream orbits and the consideration of the P-R effect would result in an increase in time needed for filling out the stream shape. But it could not change our principal conclusion on the possibility of the producing of 4 meter showers by the Geminid stream /Babadzhanov, Obrubov 1966/.

THE QUADRANTIDS

According to numerous radar measurements the semimajor axis of the Quadrantid orbits is 2.8 AU. The orbit parameters of the Quadrantid meteoroids provide a value of 3 AU. Murray /1982/ has assumed the semimajor axes of the Quadrantid meteoroids to be within 2.72 AU to 3.27 AU. According to Froeschle and School /1986/ the orbit parameters with semimajor axes from 3.25 to 3.31 AU move in resonance with Jupiter and the stream of such participles desintegrates into separate parts /arcs, over a period of 10 yr/ these parts move in orbits which differ in the argument of perihelion and in longitude of the ascending node by 180°. Hence, the effect of the resonance 2:1 with Jupiter may result in the formation of branches in the Quadrantid shower over a short time. In the range of 3.2 AU to 3.27 AU the fraction of orbits with a > 3.25 AU is ignorable. Thus the motion of only a small fraction of Quadrantid meteoroids may be determined by the resonance 2:1 with Jupiter. The orbits of the main part of the Quadrantid meteoroids will evolve in a manner shown by Hamid and Youssef /1963/; Babadzhanov and Obrubov /1979, 1980/; Williams et al. /1979/. But the dispersion of meteoroids orbits will be of great importance in the subsequent evolution of the stream. Table 4 and Fig. 4 give the results of calculations of secular perturbation of the

Table 4. Secular variations of the Quadrantid meteorid stream orbital elements. \( T=0 \) corresponds to 1950.0.

<table>
<thead>
<tr>
<th>( T )</th>
<th>( e )</th>
<th>( q )</th>
<th>( f_0 )</th>
<th>( \chi_0 )</th>
<th>( \omega_0 )</th>
<th>( R_d )</th>
<th>( R_a )</th>
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</thead>
<tbody>
<tr>
<td>-50</td>
<td>0.967</td>
<td>81.4</td>
<td>214.6</td>
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<td>54.7</td>
<td>0.2</td>
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<td>141.9</td>
<td>316.6</td>
<td>98.2</td>
<td>0.0</td>
<td>0.1</td>
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<td>0.959</td>
<td>127.6</td>
<td>115.2</td>
<td>340.3</td>
<td>96.2</td>
<td>0.1</td>
<td>0.3</td>
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<tr>
<td>-44</td>
<td>0.934</td>
<td>203.1</td>
<td>51.8</td>
<td>106.7</td>
<td>344.4</td>
<td>93.2</td>
<td>0.1</td>
</tr>
<tr>
<td>-40</td>
<td>0.712</td>
<td>145.2</td>
<td>295.8</td>
<td>360.6</td>
<td>94.8</td>
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<td>102.2</td>
<td>346.8</td>
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<td>349.3</td>
<td>91.5</td>
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<td>73.8</td>
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<td>73.1</td>
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<td>91.5</td>
<td>0.0</td>
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<tr>
<td>-28</td>
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<td>87.7</td>
<td>72.4</td>
<td>96.8</td>
<td>108.5</td>
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<td>70.1</td>
<td>97.7</td>
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<td>110.5</td>
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<td>-24</td>
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<td>50.2</td>
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<td>97.6</td>
<td>13.8</td>
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</tr>
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<td>99.6</td>
<td>0.1</td>
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<tr>
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<td>0.933</td>
<td>20.7</td>
<td>60.4</td>
<td>92.8</td>
<td>14.6</td>
<td>92.0</td>
<td>0.0</td>
</tr>
<tr>
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<td>0.960</td>
<td>12.3</td>
<td>39.1</td>
<td>87.0</td>
<td>14.8</td>
<td>103.2</td>
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<td>0.811</td>
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<tr>
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<td>135.8</td>
<td>99.0</td>
<td>0.0</td>
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<tr>
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<td>96.0</td>
<td>0.0</td>
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<tr>
<td>-10</td>
<td>0.977</td>
<td>193.2</td>
<td>50.0</td>
<td>280.2</td>
<td>163.2</td>
<td>93.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-8</td>
<td>0.920</td>
<td>207.3</td>
<td>60.4</td>
<td>283.7</td>
<td>161.4</td>
<td>92.0</td>
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</tr>
<tr>
<td>-6</td>
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<td>457.5</td>
<td>65.7</td>
<td>285.6</td>
<td>164.4</td>
<td>90.0</td>
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</tr>
<tr>
<td>-4</td>
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<td>284.4</td>
<td>165.1</td>
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</tr>
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<td>-2</td>
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<td>817.1</td>
<td>71.3</td>
<td>283.5</td>
<td>166.8</td>
<td>90.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0</td>
<td>0.683</td>
<td>977.2</td>
<td>72.5</td>
<td>282.7</td>
<td>170.0</td>
<td>93.0</td>
<td>0.0</td>
</tr>
<tr>
<td>+2</td>
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<td>1.103</td>
<td>73.3</td>
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<td>174.5</td>
<td>91.0</td>
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<tr>
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<td>1.168</td>
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<td>281.4</td>
<td>179.6</td>
<td>101.0</td>
<td>0.0</td>
</tr>
<tr>
<td>+6</td>
<td>0.678</td>
<td>1.996</td>
<td>72.4</td>
<td>280.1</td>
<td>189.7</td>
<td>110.1</td>
<td>0.0</td>
</tr>
<tr>
<td>+10</td>
<td>0.717</td>
<td>87.1</td>
<td>71.5</td>
<td>279.5</td>
<td>193.1</td>
<td>113.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

mean Quadrantid orbit by the Halphen-Goryachev method. Fig. 4 also shows the results of calculations of the orbital evolution for 10 particles having initially the same orbits using the Runge-Kutta method /Williams et al. 1979/. As is seen secular perturbations describe the changes of the orbits over a long time period rather well. On the other hand, one can see the dependence of variation of \( f \) and \( \omega \) on the position on the orbit. According to the results of Williams et al. /1979/ the semimajor axis of only one particle of a ten increases to 4.2 AU over 4000 yr in the consequence of the encounter.
with Jupiter. The amplitude of periodic changes of the semimajor axes of other particles does not exceed 0.2 AU and can be considered on the average to be constant. It can be said that for 4 millennia 10 percent of the Quadrantid meteoroids are subjected to strong Jupiter perturbations. Below we shall not take these meteoroids into account.

In the case of the Quadrants the values of \( C_1 \) and \( C_2 \) are not constant. Therefore for the construction of Quadrantid stream shape for values of \( \omega \) from 0° to 360° we used the respective values of \( e, i \) and \( \Omega \) calculated by Halphen-Goryachev method. Then as in the case with Geminids we have constructed stream normal cross-sections and the stream cross-section in the ecliptic plane /Fig. 5/ which give the notion on the stream shape /Babadzhanov, Obrubov 1986/. The distinctive feature of the Quadrantid stream is a narrow long jut near perihelion. The Quadrantid shower is observed namely at the intersection of this jut by the Earth. One more interesting feature lies in the fact that the Earth crosses the stream at four points. Two of them are very close to each other in perihelion. It means in principle that Quadrantid stream can produce eight meteor showers /Fig. 5/. The elements of meteoroid orbits intersecting the Earth’s orbit are given in Table 5.

Table 5. The elements of the Quadrantid meteoroid orbits which intersect the Earth’s orbit and corresponding showers.

<table>
<thead>
<tr>
<th>No</th>
<th>e</th>
<th>q</th>
<th>( \theta )</th>
<th>( \Omega )</th>
<th>( \omega )</th>
<th>Shower</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.68</td>
<td>1.00</td>
<td>73.3</td>
<td>99.4</td>
<td>5.6</td>
<td>K-Velids</td>
</tr>
<tr>
<td>2</td>
<td>0.97</td>
<td>0.086</td>
<td>22.2</td>
<td>71.8</td>
<td>31.2</td>
<td>B.Adriefids</td>
</tr>
<tr>
<td>3</td>
<td>0.97</td>
<td>0.087</td>
<td>23.7</td>
<td>310.0</td>
<td>148.2</td>
<td>S.S-Aquarids</td>
</tr>
<tr>
<td>4</td>
<td>0.68</td>
<td>0.977</td>
<td>72.5</td>
<td>282.7</td>
<td>170.0</td>
<td>Quadrants</td>
</tr>
<tr>
<td>5</td>
<td>0.68</td>
<td>0.998</td>
<td>72.4</td>
<td>280.1</td>
<td>189.7</td>
<td>Ursids</td>
</tr>
<tr>
<td>6</td>
<td>0.97</td>
<td>0.102</td>
<td>18.9</td>
<td>248.0</td>
<td>213.6</td>
<td>L.C-Cetids</td>
</tr>
<tr>
<td>7</td>
<td>0.97</td>
<td>0.097</td>
<td>20.9</td>
<td>130.8</td>
<td>327.0</td>
<td>N.J-Aquarids</td>
</tr>
<tr>
<td>8</td>
<td>0.68</td>
<td>0.995</td>
<td>73.5</td>
<td>100.9</td>
<td>353.6</td>
<td>Carinids</td>
</tr>
</tbody>
</table>

Table 6 gives the theoretical radiants of possible showers for the Quadrantid meteoroid stream. These radiants are close to the observed radiants of meteor showers: Daytime Arietids /Cook 1973/, \( \alpha \)-Cetids /ass. No 78, Kascheyev et al 1967/, Southern \( \delta \)-Aquarids /Cook, 1973/, Northern \( \delta \)-Aquarids /Kascheyev et al 1967/ and Ursids /Sekanina 1970/. The observed geocentric radiants and velocities for these showers are also presented in Table 6, and we can see a satisfactory agreement with theoretical calculations. Fox /1985/ found that in the past the Quadrantid orbit intersected the Earth’s orbit. Theoretical shower radiant calculated by Fox practically coincides with our theoretical and with the observed radiant of the Southern \( \delta \)-Aquarids. But that was not noticed by him.

Similar the Geminid case all the Quadrantid stream volume will be filled out by particles when the dispersion in the argument of perihelion is 360°. Because of closeness to Jupiter the dispersion of \( \omega \) in the Quadrantid stream is determined not only by the semimajor axes but also by the position of the particles. For example, for particles with equal orbital semimajor axes the dispersion in \( \omega \) may reach 150-180° for the period of 2 millennia /Fig. 4/. This dispersion can result in vide simultaneous activity of 3-4 showers. In addition the rate of dispersion of \( \omega \) can be influenced predominantly by the initial dispersion of particle orbits. As the perihelion distance of Quadrantid orbit vary from 0.08 AU to 1.1 AU the ejection velocities can be relatively large. A high initial dispersion of meteoroids orbits follow. Thus under influence of planetary perturbations the Quadrantid stream volume will be filled out very rapidly - in 5-6 millennia.
At present six meteor showers produced by the Quadrantid meteoroid stream are known. The arguments of perihelions of these showers are from 30° /Daytime Arietids/ to 330° /Northern ß-Aquarids/. Therefore we can consider that all the Quadrantid stream volume is almost filled out. It follows that a careful study of Southern hemisphere meteor showers and searches for Carinids and ß-Velids are of interest.

Thus the research carried out by us proves the separate assumptions on interrelations between Quadrantids and Ursids /Sekamina 1973/; between Quadrantids and ß-Aquarids /Hamid, Whipple 1963/; and between ß-Aquarids and Daytime Arietids /Cook 1973/.

Mass segregation in the Quadrantid stream was found by radar observations /Kascheyev, Lebedinets 1960/. This segregation was satisfactorily explained by the ejection of meteoroids from the parent body, light pressure, P/R effect and planetary perturbations /Hughes et al 1981; Babadzhanov, Obrubov 1983; Fox 1983/.

According to visual observations of Quadrantid shower since 1835 up to the present Hindley /1972/ has found the regression of the maximum activity date, which is equal to 0.28° per century. From radar observations this regression is found equal to 0.31° +/− 0.17 per century /Hughes 1972/. Taking into consideration a high inclination of Quadrantid orbits it can be supposed that the regression in date is equal to the regression of the longitude of orbital ascending node. The calculated regression of ascending node is in the range from 0.37° to 0.49° per century /Babadzhanov, Obrubov 1980; Hughes et al 1981; Murray 1982/. This gives evidence to the fact that the regression of the maximum activity date is the result of planetary perturbations, mainly by Jupiter.

First observations of the Quadrantid shower were carried out in 1830 /Hindley 1972/; Babadzhanov and Obrubov /1973/; Babadzhanov et al /1980/ and Murray et al /1980/ supposed that the observations of the shower became possible due to the approach of the stream to the Earth's orbit. These authors drew a conclusion that Quadrantid shower may be active during about 3 centuries. However, Astapovich and Terentjeva /1968/ contend that the bolides observed in XI century on 9-th of January belong to the Quadrantids. Now we can suppose the possibility of observations of Quadrantid meteoroids in the XI century because the dimensions of the cross-section of the stream in the ecliptic plane are much larger than had been thought earlier. Rich displays of the ß-Aquarids in the VIII century are indicative of such conclusion /Astapovich, Terentjeva 1968/.

**Table 6. Theoretical and observable radiants of meteor showers produced by the Quadrantid meteoroid stream. V in kms.**

<table>
<thead>
<tr>
<th>Daytime Arietids</th>
<th>Daytime ß-Cetiids</th>
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<tbody>
<tr>
<td>λ₀</td>
<td>72°</td>
</tr>
<tr>
<td>δ₀</td>
<td>40°</td>
</tr>
<tr>
<td>λ₁</td>
<td>23°</td>
</tr>
<tr>
<td>δ₁</td>
<td>41</td>
</tr>
<tr>
<td>q</td>
<td>0.07</td>
</tr>
</tbody>
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Southern Quadrantids

<table>
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<tbody>
<tr>
<td>λ₀</td>
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</tr>
<tr>
<td>δ₀</td>
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</tr>
<tr>
<td>λ₁</td>
<td>-15°</td>
</tr>
<tr>
<td>δ₁</td>
<td>42</td>
</tr>
<tr>
<td>q</td>
<td>0.07</td>
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</table>

Northern Ursids

<table>
<thead>
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<th>Obs.</th>
</tr>
</thead>
<tbody>
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<td>λ₀</td>
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<tr>
<td>δ₀</td>
<td>45°</td>
</tr>
<tr>
<td>λ₁</td>
<td>-56°</td>
</tr>
<tr>
<td>δ₁</td>
<td>41</td>
</tr>
<tr>
<td>q</td>
<td>?</td>
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</tbody>
</table>

Southern ß-Velids

<table>
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<th>Obs.</th>
</tr>
</thead>
<tbody>
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<td>λ₀</td>
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</tr>
<tr>
<td>δ₀</td>
<td>152°</td>
</tr>
<tr>
<td>λ₁</td>
<td>-60°</td>
</tr>
<tr>
<td>δ₁</td>
<td>41</td>
</tr>
<tr>
<td>q</td>
<td>?</td>
</tr>
</tbody>
</table>

Theor. Obs.

| λ₀ | 281° | ? |
| δ₀ | 152° | ? |
| λ₁ | -60° | ? |
| δ₁ | 41 | ? |
| q | ? | ? |

Carinids

Southern Quadrantids

<table>
<thead>
<tr>
<th>Theor.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
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<td>λ₀</td>
<td>281°</td>
</tr>
<tr>
<td>δ₀</td>
<td>152°</td>
</tr>
<tr>
<td>λ₁</td>
<td>-60°</td>
</tr>
<tr>
<td>δ₁</td>
<td>41</td>
</tr>
<tr>
<td>q</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 6 also gives semimajor axes, maximum and minimum of inclinations and the stream width along the Earth's orbit. Table 7 shows that about 30% of showers are produced by flat streams (i < 5°) — by thick streams (i/6 - 10°) — by streams of about the same width and thickness (i/6).

Let's consider how many meteor showers may be produced by one meteoroid stream. When the stream orbit lies in the ecliptic plane it may produce two showers if q < 1 AU and one shower if q > 1 AU. As the formula 6/10/ show if q > 1 AU the meteor stream can produce 4 or 8 showers. The numbers of meteor showers N for each stream are given in Table 7. The well-known meteor stream of Encke comet produce 4 meteor showers: the Northern and Southern branches, and the daytime ß-Taurids and ß-Psceids. The ß-Aquarids and ß-Orionids, which have the Northern and Southern branches, are referred to the streams producing 4 showers. The possibility of the producing of 8 meteor showers by one stream is illustrated by Quadrantids. The ß-Aquarids and ß-Cetiids are also referred to this type of streams.

Qualitative investigation of the short-period meteoroid streams show that their dimensions may be large. This fact should be considered while estimating the stream volumes, space densities and stream masses. Moreover it is necessary to take into account the observations of all possible showers, which can be produced by the meteoroid stream considered.
Table 7. Semimajor axes, maximum and minimum of inclinations, thickness and number of possible meteor showers - N for short-period meteoroid streams

<table>
<thead>
<tr>
<th>Shower</th>
<th>a (AU)</th>
<th>h°</th>
<th>h</th>
<th>N</th>
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<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Virginiids</td>
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<td>0</td>
<td>2</td>
</tr>
<tr>
<td>δ-Leonids</td>
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<td>0</td>
<td>2</td>
</tr>
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<td>Camelopardalis</td>
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<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>α-Capricornids</td>
<td>1.2</td>
<td>0</td>
<td>0</td>
<td>2</td>
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<td>S.Piscids</td>
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<tr>
<td>Jun. Bootids</td>
<td>3.3</td>
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The phenomenon of formation of shower branches may be widely spread. So it is necessary to continue searching relative showers. In conclusion we would like to emphasize the fact that if we know the existence of the two branches of a shower then the relative showers with intermediate values of perihelion arguments must be active.

Thus, because of the differences in the election velocities, light pressure and times of ejection an initial dispersion of meteoroid orbits is formed. Subsequently under planetary and non-gravitational perturbations this dispersion becomes so great that a meteoroid stream produces several relative meteor showers which are active at different times of the year.

References


Cook A.F. 1973, In: Evolutionary and Physi-
Discussion:

Lindblad: This is a very interesting paper. In your computations you use two integrals of motion derived by Moiseev (1945) and Lidov (1963). Since these papers are not easily accessible to most meteor workers, it would be desirable that a review of them be given at a future meteor conference.

Babadzhanov: I shall do this in the nearest future.

Olsson-Steel: This is an interesting and important paper. For this to be a complete theory, I believe that there must be a good explanation of how the required initial dispersion in semimajor axes is achieved; do you think that this has been done?

Babadzhanov: Yes, I think so. However, if any initial dispersion in semimajor axes and other orbital elements exists, then, under the planetary perturbations, this dispersion becomes so large that each meteoroid stream produces several meteor showers.

Simek: Can you compare the physical characteristics of parent shower with those of shower branches? I have in mind the mass-distribution index, the density of meteoroids and other parameters resulting from meteor spectra?

Babadzhanov: We have compared the physical characteristics of different showers produced by the same meteoroid streams. For example the densities of meteoroids of Quadrantids and delta-Aquarids are very close. But we have not compared the mass-distribution indices of shower branches of twin showers so far.

Stohl: From observations of the Taurid complex it appears that several showers forming this complex are smoothly connected each with the others (S and N Taurids, N and S Chi-Orionids etc.), forming thus just one very prolonged stream. Can your calculations explain this feature or do you obtain a few separate branches of a stream in each case?

Babadzhanov: Our calculations can explain all the features of the Taurid complex, but it is necessary to know the initial distribution of the meteoroid's semimajor axes.

Babadzhanov: I shall do this in the nearest future.
Resonance Intermittance Causes the Gravitational Splitting of Meteor Streams

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Abstract

The dynamical evolution of meteor stream particles in resonance appear to be affected by the same resonance mechanisms as resonant asteroids. Crossing of separatrix like zones appears to be crucial for the formation of arcs and for the dissolution of streams.

Investigating the orbital evolution of known resonant meteor streams and of model streams, we have found examples for such a transitory arc formation. The orbital inclination of a meteor stream appears to be a critical parameter for arc formation.

1. - INTRODUCTION

The frequency distribution of semi major axes of meteor streams shows minima at mean motion resonances with Jupiter (see Lindblad, 1972), like, but however less striking, as in the case of asteroids. Hence, the long term evolution of meteor stream particles close to resonance is affected by the same resonance mechanism as the dynamical evolution of resonant asteroids. Of course, since meteor streams particles mostly move on orbits with high eccentricities and inclinations their long term evolution has been investigated very little in celestial mechanics as such orbits can be hardly approximated by classical series expansions. In addition, there are non-gravitational forces like the Poynting-Robertson drag and the solar wind which cause the orbits of small particles to slowly spiral into the sun. On the other hand, the radiation pressure exerts a force consisting in a reduction of the gravitational force exerted by the sun on the particle. Radiation pressure depends on particle cross-section. Particles with different masses may feel different accelerations towards the Sun.

Hence, radiation pressure is expected to cause a mass segregation within a stream during its formation and after that a further mass segregation might result from Poynting-Robertson and solar wind drags. Such a mass segregation is observed in the Quadrantid stream (Hughes and Taylor, 1977). Explanations for this observation are proposed by Hughes et al (1981) and by Babadzhanov and Obrubov (1983).

Besides all these non-gravitational mechanisms, mean motion resonance with Jupiter might be responsible for splittings of streams.

How a meteor stream can split up into separate arcs was demonstrated by Froeschlé and Scholl (1986) in a model calculation. Froeschlé and Scholl placed a highly inclined (\(i = 68^\circ\)) and highly eccentric (\(e = 0.68^\circ\)) model meteor stream in the 2/1 resonance region with Jupiter. Jupiter perturbations alone without close approaches to Jupiter set up the splitting of the model meteor stream into arcs.

The splitting is caused by the particular dynamics of resonant motion. The important variable which determines the splitting, is the longitude of ascending node \(\Omega\) of a stream particle's orbit.

Outside a resonance region, \(\Omega\) regresses almost uniformly due to Jupiter perturbations, in particular due to orbital momentum transfer. The corresponding rate \(\dot{\Omega}\) depends mainly on the semimajor axis of a particle's orbit. We like to emphasize that outside of a resonance region, \(\dot{\Omega}\) does not depend on the mean longitude of a particle with respect to Jupiter's mean longitude. In other words, the average momentum transfer to the particle's orbit which determines \(\dot{\Omega}\) is basically the same for all stream particles.
independent of the location of a particle in its orbit. As a consequence, the whole stream precesses without splitting up.

In a resonance region, on the other hand, the situation might be different: The average angular momentum transfer might be strongly dependent on the location of a particle in the stream. Hence, the nodal lines of particle orbits might precess with very different speeds and their motion might even become prograde or librate. This is the basic mechanism for a stream to split into arcs. An arc consists of particles with about the same orbital rate which is very different from orbital rates of other particles of the original stream. Over which timescales such arcs remain stable is known only within the frame of the model, of course, which in particular does not include collisions among stream particles and which does not include the Poynting-Robertson effect.

In section II, we describe the model and some topological features extrapolated from the planar circular resonant restricted three body problem.

In section III, spectacular splitting in the 2/1 resonance for Quadrantid-like meteor streams is shown. A long term evolution reveals a resonance intermittance due to some crossing of a separatrix like zone.

In the last section, results of the orbital evolutions of 7 known resonant meteor streams are described.

2. DESCRIPTION OF THE MODEL

We first restrict our attention to the planar case since it leads to a fundamental set of orbits which will be used as a paradigm to explain the various behaviours found in the three dimensional model. For an approximate ratio \((p + q)/p\) of the mean motion of an asteroid to that of Jupiter, Schubart presents the following system of canonical equations for the planar elliptic problem:

\[
\frac{dK}{dt} = \frac{\partial H}{\partial \nu}, \quad \frac{ds}{dt} = \frac{\partial H}{\partial \sigma},
\]

\[
\frac{d\nu}{dt} = -\frac{\partial H}{\partial K}, \quad \frac{d\sigma}{dt} = -\frac{\partial H}{\partial S},
\]

with the time, \(t\), the Hamiltonian \(K = \sqrt{a(p + q)/p} - \sqrt{a} \cos \phi\), the osculating elements being defined by:

- \(a\) semi-major axis,
- \(e = \sin \phi\) eccentricity,
- \(M\) mean anomaly,
- \(l\) mean longitude. The subscript \(j\) denotes Jupiter's elements.

Schubart (1964, 1978) averages the Hamiltonian \(H\) over the commensurability period \((p + q)2\pi\) of the short period argument \(M\):

\[
H = \frac{1}{2\pi(p + q)} \int_{0}^{2\pi(p + q)} H(M, K, S, \nu, \sigma) dM
\]

Hence \(H\) is independent of time and therefore \(H\) is an integral of motion in the average sense. If in addition \(e_j = 0\) then \(K\) is a second integral. Fig. 1 displays the well known topology in the plane \(X = \sqrt{2S} \cos \sigma\) and \(Y = \sqrt{2S} \sin \sigma\):

Banana shaped orbits and circular orbits appear in the \(S, \sigma\) space. A zero frequency orbit called the separatrix devies the \(S, \sigma\) space in three regions where orbits behave distinctly.

Region I corresponds to the inner portion of the bifurcation curve around the point \(a\), where the apocentric librators occur. Pericentric librators on banana-shaped trajectories occur around \(p\) in region II. The outer circulators fill region III outside of the bifurcation curve.

In the circular averaged model \(e_j = 0\), orbits remain in their corresponding region. In the more general model with \(e_j \neq 0\) and without averaging, orbits can cross the bifurcation curve and consequently can change their behaviour. In particular, librators can become circulators and vice versa.

It is clear that Schubart's topology displayed in Fig. 1 is only valid for the circular planar averaged model.

Only in this model, the problem of resonant motion is fully integrable. The critical bifurcation point is called a homoclinic point in modern dynamics (Arnold, 1978). It is well known that integrable systems are not generic, i.e., small perturbations can destroy the integrability, and the separatrix or homoclinic orbit can cause wild regions with chaotic behaviour (Arnold, 1978). This peculiar behaviour for Schubart's topology was displayed by Froeschlé and Scholl (1977) in the elliptic averaged case.

Besides ellipticity, also non-averaging or non-coplanarity destroys the integrability. For the case of non-coplanarity we will show that Schubart's topology displayed in Fig. 1 remains valid to some extent and can be regarded as a good paradigm in order to understand and to describe the behaviour of resonant orbits in the three-dimensional elliptic averaged case.

For this more general case, Schubart (1978, 1979) extended the planar model. The six variables in his differential equations are:
Fig. 1 - Trajectories in $S - \sigma$ space based on "Schubart's à la Poincare"'s model for 2/1 planar circular resonant orbits.

$$G = \sqrt{a(1 - e^2)}$$
$$\mu = \frac{l - lp + q}{p}$$
$$\Psi_1 = \frac{e \cos \hat{\omega}}{}$$
$$\Psi_2 = \frac{e \sin \hat{\omega}}{}$$
$$\Psi_3 = \frac{\tan(i/2) \cos \Omega}{\tan(i/2) \sin \Omega}$$

$\hat{\Omega}$ is the longitude of the ascending node of the asteroid's orbit with inclination $i$ against Jupiter's orbit reckoned from Jupiter longitude of perihelion.

The critical argument $\sigma, r$ and $\mu$ are such that

$$\sigma = -(\hat{\omega} + \mu p/q)$$
$$\tau = -\Omega - \mu p/q$$

Froeschlé and Scholl (1986) have investigated the behaviour of orbits starting with different values of $a, e, i$ and eight representative geometric configurations for the angles $(\hat{\omega}, \hat{\Omega}, \mu, r, \omega)$ through the computation of 96 orbits at the 2/1 Kirkwood gap over 17000 years. A classification with respect to the behaviour of $\omega$ and $\hat{\omega}$ yields 5 classes and three major mechanisms determining orbital stability: $\sigma$ libration, $e - \omega$ phase coupling and $\omega$ libration. But for the resonant meteor streams the relevant variable is the critical argument $\mu$ whose variations may lead to a spectacular breaking.

3. - RESONANCE INTERMITTANCE AND GRAVITATIONAL SPLITTING OF METEOR STREAMS

According to Hughes et al (1979), the Quadrantid stream has the following orbital parameters with respect to ecliptic and equinox 1950: $(\omega = 170^\circ 4, \Omega = 292^\circ 6, i = 71^\circ 4, e = 0.681, a = 3.064)$. Using the Schubart averaged program, we have integrated five different streams with about the same initial conditions but situated within the resonance. We used 12 starting values $\mu = 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ, 360^\circ$ in order to represent a stream. We have found five modes of nodal motion depending on the values of the resonance variable $\mu$: three modes of nodal motion: either nodal regression with jumps of $180^\circ$ or temporary libration, or progression occurs. Consequently a stream may break up into two isolated arcs. Fig. 2 shows schematically the starting configuration of a stream and the arcs formed from this stream in a perspective view.

This stream has its ascending node in the lower part of Fig. 2 outside of Jupiter's orbit. The dashed part of the stream lies below Jupiter's orbital plane. The circles on the initial stream refer to the stream's portion with $\mu$ ranging from $-60^\circ$ to $+90^\circ$ (regression). Asterisks refer to the portion with $\mu$ ranging from $150^\circ$ to $210^\circ$ (progression).

Fig. 2 - The initial stream and the orbits of two resulting arcs A and B after about 1000 Jupiter revolutions. Dashed parts of an orbit lie below Jupiter's orbital plane. Circles on the initial stream refer to the stream's portion with $\mu$ ranging from $-60^\circ$ to $+90^\circ$ (regression). Asterisks refer to the portion with $\mu$ ranging from $150^\circ$ to $210^\circ$ (progression).
B is expected. On the other hand, arc A will dissolve faster since the nodal rates of arc A orbits depend on the variable $\mu$.

To locate the regions of the $a$, $e$, $\omega$, $i$ phase space where streams break up into arcs is difficult since we are concerned with a system with three degrees of freedom and therefore Fig. 1 can only be a crude approximation for describing the topology of the system. Obviously there exist separatrix-like surfaces where chaotic motion is expected. We have found such orbits with temporary progression of $\Omega$ with intermittent jumps.

It is interesting to note that the jumps in $\Omega$ and in eccentricity are not related to a crossing of the separatrix-like zone in Schubart's $S - \sigma$ plane mentioned above. We investigated the orbital evolution in a different plane, namely in the $\Psi_1 - \Psi_2$ plane, defined above.

Like in Schubart's $S - \sigma$ plane, resonant motion represented in the $\Psi_1 - \Psi_2$ plane can show three modes: progression, regression, and libration. Alternators between these three modes are also known to occur like in the $S - \sigma$ plane (e.g. Froeschlé and Scholl, 1977). Figure 3 shows that our orbit is such an alternator.

The trajectory starts at point A. Circles represent the trajectory for the first 100,000 yrs while crosses represent the trajectory for the remaining period. In the beginning, the orbit librates over one cycle on a banana-shaped curve.

![Figure 3 - An orbit with a temporary progression of $\Omega$.](image-url)

The starting values are $a = 3.28$ AU, $e = 0.68$, $i = 71^\circ$, $\Omega = 0^\circ$, $\omega = 170^\circ$ and $\mu = 210^\circ$. The orbit starts at point A. The symbol $\circ$ is used to plot the trajectory during the first 100,000 yr. After 100,000 yr, the orbit enters the retrograde circulation region. After two circulations, the orbit appears to leave this region. Nothing can be predicted for the further evolution. Obviously, like in Schubart's $S - \sigma$ space, there is also in the $\Psi_1 - \Psi_2$ space a separatrix-like zone. Crossing this zone changes the character of orbital evolution. We conjecture therefore that calculating Liapunov's maximal characteristic exponent would reveal a chaotic orbit (see for instance Froeschlé, 1984).

4. - RESONANT ORBITAL EVOLUTION OF SEVEN KNOWN METEOR STREAMS

In table 1, the orbital parameters of seven $(p + q)/p$ resonant streams are given. We have found (Scholl and Froeschlé, 1987) the following

June Bootius in 2/1 resonance: Arcs may show up after time scales of $10^8$ years. Since the Poynting-Robertson effect would cause the dispersion of this meteor stream on such time scales, we do not expect to observe arcs of this stream. On the other hand, fast close approaches of stream particles in the range $-90^\circ \leq \mu \leq -60^\circ$ will form a hole in the stream. If it is possible to make observations in this region of the stream, an age of the stream might be estimated, since the formation of the hole takes less than 200 years.

The Annual Andromedis stream will not split up into arcs due to the resonance mechanism. We think that its inclination of $12^\circ$ is too low to show this effect. This will be a dispersion of the portion of the stream between $30^\circ \leq \mu \leq 120^\circ$ due to the comparatively fast precessional rates for nodal lines of particle orbits. Changing slightly the semi-major axis of this stream from $a = 3.29$ AU to $a = 3.25$ AU does not yield quantitatively different results.

The low inclination ($i = 4^\circ$) of the 3/1 resonant Librids stream does not favour a fast splitting into arcs. This stream will disperse rather slowly. After some $10^3$ years, the stream portions between $150^\circ \leq \mu \leq 180^\circ$ will disappear because of the comparatively fast rate of $\dot{\Omega}$.

The June Lyris streams has large inclination ($i = 44^\circ$) and high eccentricity ($e = 0.67$). Nevertheless, no fast splitting into arcs on timescales of the order of $10^5$ years like in the case of the Quadrantids- like stream occurs. The nodal lines of all test particles regress with rates for nodal lines of particle orbits. Changing slightly the semi-major axis of this stream from $a = 3.29$ AU to $a = 3.25$ AU does not yield quantitatively different results.

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The highly inclined July Phoenicids stream at the 3/1 resonance reveals the regression of the nodal lines with jumps which characterizes the splitting into arcs. However, unfortunately, all orbits show the jump. Hence, no splitting into arcs can be expected.

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Close approaches to Jupiter cause the formation of holes in the 7/3 resonant December Phoenicida stream within 200 years. The remaining portions will also be dispersed due to close Jupiter encounters within a few $10^3$ years. Due to the hole formation, short arcs of this stream might form. A more detailed examination of the dispersion of this stream due to close Jupiter approaches and a comparison with observations might yield estimations about a lower or an upper limit of the stream's age.

Such an estimation seems in particular possible for the 3/2 resonant Pegasids stream. All our model particles had a fast close encounter with Jupiter within 200 years. The Pegasids are located outside of the 3/2 libration region which protects the Hilda-type asteroids from close encounters with Jupiter (Schubart, 1968).

5. - CONCLUSIONS

These seven known meteor streams located in mean motion resonances with Jupiter do not reveal the same kind of splitting into arcs discovered by Froeschlé and Scholl (1986) for a Quadrantid-like meteor stream. This latter model stream splits into arcs solely due to resonance mechanisms. No close approaches to Jupiter are involved. In the case of these seven known meteor streams, on the other hand, arcs may form in some cases due to Jupiter approaches. These approaches cause the formation of holes in a stream. Hence, the remaining particles of the stream do form arcs. This mechanism to form arcs is, of course, quite different from the resonance mechanism causing the splitting of the Quadrantid-like stream, which is based on the different motions of nodal lines of stream particles. The close approach mechanism discovered for some of the seven known meteor streams can be used to estimate upper limits for ages of meteor streams. Such an age estimation would be a premiere in the field of meteor streams.

REFERENCES


DISCUSSION

Kresák: What is the width of the resonance zone in comparison with the mean error in the semimajor axis as determined from the observations? I mean whether you can identify individual librating objects.

Froeschlé: The problem of identifying single observations with the arcs we predict has still to be investigated.

Babadzhanov: According to observations the semimajor axis of Quadrantids is in the range 2.79 to 3.27 AU. Thus your results and conclusions on the disintegration of the stream into separate arcs refer only to a small part of the stream meteoroids, which have a $\geq 3.22$ AU. But you show that this is one possibility of shower branch formation.

Froeschlé: Thank you for your comments. Hence the effects we discussed might be real.

Lindblad: In your interesting study you have investigated the Quadrantids and seven other meteoroid streams. With the exception of the Andromedids these streams are of low activity, and thus unfortunately we have no accurate photographic orbits or checking the computations. My question is, why you have not studied the Southern Delta Aquarids, which is the most prominent meteor shower observed in the southern hemisphere, and which is located exactly at one of the Kirkwood resonances (Lindblad, B.A., 1952, Observatory).

Froeschlé: According to the Fox, best in Uppsala II, it is close, but not within the 5/2 Kirkwood gap.
THE DISPERSAL OF METEOROID STREAMS BY RADIATIVE EFFECTS

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A major problem in meteor astronomy is why the orbits of meteoroids within particular streams are so dispersed. For streams with aphelia well within Jupiter (such as the Geminids) planetary perturbations cause insignificant dispersion but can accommodate the required motion of the nodal heliocentric distance to explain why the Geminids were not observed prior to the 1860's. The spread in the orbits would only require unreasonably large ejection velocities from the parent. Another dispersal mechanism is therefore required.

By incorporating perturbations due to the Yarkovsky-Radzievskii effect into the model the Geminid dispersion can be understood; by including also the effects of the radiation pressure and Poynting-Robertson forces the main observed characteristics of the stream (shower duration variation with magnitude; skew rate profile; changes in mass distribution and radiant diffuseness as the shower progresses) are explicable. The necessary spin rates (about 2000 rev/sec for 1 mm and 1000 rev/sec for 1 cm radius meteoroids) would be attained within a thousand years of release from the parent body, due to spin-up under solar radiation pressure. It therefore appears that the Yarkovsky-Radzievskii effect is an important source of stream dispersion which has been hitherto neglected, but should be included in future models.

Prologue

"There is no question that meteoroids are dispersed in orbital elements much faster than perturbations, the Poynting-Robertson effect, and collisions can explain. I have tried for many years to find other physical effects that can limit the dispersion. ... I suspect it is some phenomenon of light pressure on spinning grains as Upik has suggested." Whipple, 1972.

1. Factors which may cause stream dispersal

For some years there has been a realization that the member meteoroids of particular streams are rather more dispersed in orbital elements (in particular the semi-major axis) than can easily be explained or understood in terms of well-established dispersed mechanisms, as follows. Despite the fact that zodiacal dust particles limit the physical lifetimes of meteoroids of radius 100μm - 10μm (Dohnanyi, 1978; Leinert et al., 1983; Steel and Elford, 1986), these catastrophic impacts occur on a much longer time-scale than the age of meteoroid streams so that they are not an important source of dispersion; non-catastrophic collisions also cannot cause significant dispersion since the dust involved is many orders of magnitude smaller in mass than the meteoroids (Jones et al., 1985; Olsson-Steel, 1987a). Although streams with orbits like short-period comets (aphelia near Jupiter) are quickly scattered by planetary close encounters and are the major source of the sporadic background (Olsson-Steel, 1986), there are some streams which cross the giant planets and yet have larger dispersions than can be explained by planetary perturbations. For example, the Halleyid stream would not be dispersed significantly, in the same way as the orbit of P/Halley is stable even under planetary close encounters (Olsson-Steel, 1987b), although the stream width may be caused by the comet having a librating orbit (McIntosh and Hajduk, 1983); another example is the Perseid stream, the Earth being the only planet which the stream approaches so that the planetary perturbations are too small to explain the shower duration (B.A.Lindblad, personal communication). For streams with aphelia well within Jupiter's orbit, such as the Geminids (Q = 2.6 AU), the dispersion in semi-major axis caused by planetary perturbations is certainly very small since the terrestrial planets have little effect: it has been shown (Jones, 1985; Jones and Wheaton, 1985; Hunt et al., 1985) that the dispersion produced is only about one-fiftieth of that required by the shower duration. (However, these exact numerical integrations have been able to demonstrate that the nodal heliocentric distance was not close to 1 AU until just over a century ago, and hence explain why the Geminid shower was not observed until the 1860's: Jones, 1982, 1985; Fox et al., 1982, 1983; Babadzhanov and Obrubov, 1980, 1984). Since the spreading of the Geminid orbital energies by the planets is so small, this stream is of considerable interest as regards an understanding of the dispersal of streams in general: knowing that the scatter due to gravitational interactions is certainly too small to be of consequence, the origin of the observed dispersion can be looked for elsewhere.

The next dispersal agent to be considered is the effect of ejection velocities from the parent, such that the stream is formed with a spread in orbital energies. Using the standard ejection velocity formula due to Whipple (1951) it has been shown that the calculated velocities are too small to explain the observed shower duration by an order of magnitude (Fox et al., 1983; Jones et al., 1985), however, more recently it has been demonstrated by Jones and Hawkes (1986) that a better (but still inadequate) fit to the observations is gained by including the effect of the initial differences in the orbital elements (due to the ejection mechanism) upon the subsequent orbital evolution under planetary perturbations. Thus, to date models relying upon ejection velocities have been unable to explain the observed parameters of the Geminid stream.

Radiative forces have been considered by many authors in investigating the evolution of meteoroid streams, and in particular orbital decay under the Poynting-Robertson (P-R) effect has been recognized as being important in causing meteoroids to gradually spiral in towards the Sun before they are eventually destroyed in collisions with the zodiacal dust. Not so well recognized has been the role of radiation pressure (as opposed to ejection velocities) in causing loop formation in streams (Carusi et al., 1983). The linear dust trails discovered in the orbits of various periodic comets by Sykes et al. (1986), which consist of submillimetre (but not much smaller) meteoroids and hence would be observed on the Earth as faint radar meteors, are strongly asymmetric: the trails extend rather further behind the comets than in front, and this vividly demonstrates that radiation pressure (which always causes the dust to lag behind the comet) is important in promoting loop formation, and appears to dominate ejection velocities (which can cause meteoroids to lead or lag the comet).
If the Geminid stream were gradually formed over a length of time > 10^4 years (i.e. meteoroid ejection continues unabated over this entire period) then it is just possible that the ∼1 week duration of the radio meteor shower could be explained by the P-R effect causing spreading in the orbital energies, due to the earliest-released having suffered more orbital contraction than the later-released particles; however, then the visual shower should be much shorter than the 3–4 days actually seen, so that the P-R effect cannot in isolation explain the shower characteristics, although it may aid the fit between planetary-perturbation/ejection velocity models and the observed shower (Jones and Hawkes, 1986).

To date, models for meteoroid stream evolution have not included the Yarkovsky-Radzievskii (Y-R) effect, which received its modern introduction from Upik (1951) and was also described by Radzievskii (1952). It is shown briefly in this paper, and in more detail by Olsson-Steel (1987a), that the Y-R effect can easily explain the observed dispersion in the Geminid stream, and by implication in other meteoroid streams, for plausible physical parameters and spin rates of the meteoroids; in fact for the Y-R effect not to be an important source of dispersion would require either very small (ω < 1 rad/sec/year) or very large (ω > 10^8 rad/sec) spin rates. If the conclusions of this paper are correct then the Y-R effect is the predominant stream-dispersal agent in the inner solar system, as functionally by Whipple (1972), and must be included in future models of stream evolution if these are to be realistic.

2. Radiative forces upon meteoroids

Burns et al. (1979) have reviewed the forces acting upon solid particles due to the solar radiation field, and investigated the relative importance of each as a function of particle size. The expressions for the three radiative forces favoured by the present author are:

Radiation Pressure (RP):

\[ F_R = \left( S \frac{Q}{\pi r^2} c \right) \left( 1 - \frac{V_r}{c} \right) \]  (1)

Poynting-Robertson (due to the different Doppler shifts, and hence momentum, of forward- and backward-emitted photons):

\[ F_P = \left( S \frac{Q}{\pi r^2} c \right) \left( V_r + \frac{V_L}{c} \right) \]  (2)

Yarkovsky-Radzievskii (due to the varying amounts of momentum emitted in different directions by spinning, and hence non-isothermal, meteoroids):

\[ F_Y = \left( 8 \pi \frac{r^3}{T^4} \right) \left( \frac{\alpha T^2 \Delta T}{c} \cos \epsilon \right) \]  (3)

Here \( S \) is the solar flux at the position of the meteoroid (\( S = 1.37 \text{ kW/m}^2 \) at 1 AU), \( Q \) is a scattering coefficient \((Q = 1 \text{ particle/g} \text{ cm}^2\) throughout), \( r \) is the radius of the meteoroid (assumed to be spherical), \( c \) is the velocity of light, \( V_L \) is the heliocentric radial velocity of the meteoroid, \( V_r \) the transverse velocity, \( \alpha \) is the Stefan-Boltzmann constant, \( \epsilon \) is the meteoroid obliquity (the angle between its spin axis and the pole of its orbit), \( T \) is the meteoroid mean temperature, and \( \Delta T \) is the temperature difference across its surface, derived from:

\[ \Delta T = \left( \frac{1 - \varepsilon}{\varepsilon} \right) \frac{S}{\omega} \]  (4)

where \( \varepsilon \) is the albedo. The thermal inertia \( (1/\gamma) \) is defined as: \( (k = \text{thermal conductivity}; \rho = \text{density}; C = \text{specific heat}) \)

\[ (1/\gamma) = \left( K \rho C \right)^{\frac{1}{2}} \]  (5)

The temperature is:

\[ T = \left( \frac{1 - \varepsilon}{\varepsilon} \right) \frac{S}{4 \omega} \]  (6)

as long as \((\Delta T / T)\) is small, as is the usual case.

These three forces have quite different influences. \( F_R \) acts directly away from the Sun; if the Doppler term is neglected then \( F_P \) effectively results in a constant reduction factor on the solar gravitational attraction: the meteoroid continues to move on an elliptical orbit. \( F_Y \) acts both radially and transversely, but is restricted to the particle's orbital plane; as is well-known, it causes a gradual inspiralling towards the Sun as the meteoroid's orbital energy declines. However, \( F_Y \) acts in all three dimensions and is diffusive in nature; it can lead to either an increase or decrease in the orbital energy (depending upon the spin direction) and will cause gradual spreading of all of the orbital elements of meteoroid streams.

3. Expected physical and dynamical parameters

In order to calculate the magnitudes of the radiative forces, estimates of the meteoroidal physical and dynamical parameters are required.

The density of Geminid meteoroids of mass \( \sim 1g \) is rather higher than that of most meteors, having a value of about 1.06 g/cm^3 (Hughes, 1978); this value, which may reflect the small perihelion distance of the Geminids, will be used throughout. The specific heats of ices, silicates and iron are of the order of 1000 and 500 J/kg/K respectively; the exact value used is unimportant since the thermal conductivity of the meteoroidal material is highly uncertain. Terrestrial silicates have a conductivity \( K = 3.5 \text{ W/m/K} \), but these are close-packed structures; the above values for \( \rho \), \( C \) and \( K \) would render a thermal inertia \((1/\gamma) = 2000 \text{ J/kg/K} \) (these units are used for this parameter throughout). However, the thermal conductivity of the meteorial material is rather higher than that of most meteors, having a value of about 1 kg/m/K (Squyres et al., 1985; Wood, 1986) which would then give \((1/\gamma) = 300\); free meteoroids might have an even lower conductivity \( C \), giving the thermal inertia even further. This, Geminid meteoroids may be expected to have thermal inertias of the order of 100 - 500.

Meteoroidal albedoes are uncertain. The nucleus of P/Halley has \( A < 0.04 \) (Keller et al., 1986), whilst IRAS observations of the zodiacal dust cloud have rendered \( A = 0.07 \) (Hauser et al., 1985), and other zodiacal light data and theoretical modelling give similarly small albedoes (Hanner et al., 1987). A meteoroidal albedo of 0.1 will be adopted as nominal.

The meteoroid spin angular velocity \( (\omega) \) is now required. There have been numerous arguments in the past in favour of high meteoroid spin rates, of the order of \( 10^4 - 10^5 \text{ rad/sec} \). These arguments include the fragmentation and bursting of visual/photographic meteors, the initial widths of radar meteor trains (Hawkes and Jones, 1978), and theoretical arguments based upon spin-up in the solar radiation field either via a 'windmill' or a 'paddlewheel' effect (e.g. Radzievskii, 1954; Donnany, 1978; Ratcliff et al., 1980). It is quite simple to show that it is solar radiation pressure which dominates the torque upon meteoroids (rather than the solar wind, or collisions with smaller particles), and the spin-up proceeds at a rate (Olsson-Steel, 1987a):

\[ \omega_S / \omega = 15 G S Q / 8 \pi c \rho r^2 \]  (7)

where \( g \) is a factor describing the efficiency of the windmill/paddlewheel. It is to be emphasized that \( g \) is not well-known and so far only crude estimates have been made (Paddack and Rhee, 1976); hence a value of \( g = 0.001 \) will be assumed. Using such a small efficiency factor one finds from (7) that at 1 AU:

\[ \omega_S / \omega = 100 \text{ rad/sec/year} \] (r = 1mm)

\[ \omega_S / \omega = 1 \text{ rad/sec/year} \] (r = 1cm)

so that very high spin rates would be attained within
a few hundred years; of course, the torque upon an individual meteoroid would not continue in the same sense or with the same magnitude over its lifetime, since variations in its surface structure and refractive index characteristics will occur due to sputtering, collisions, etc. In addition, the spin axis will precess at a rate:

$$\omega_p = 15.9 \frac{Q}{8c} \rho r^2 \omega$$

(8)

which implies that the spin axis will precess about the Sun-meteoroid line several times in each orbit, leading to a random-walk type of movement away from the mean stream orbit.

As briefly mentioned above the Y-R effect is due to the fact that the meteoroid will not be isothermal if it is spinning sufficiently quickly. This requires a spin rate of:

$$\omega_s > \frac{4\pi K}{\rho r^2 C}$$

(9)

which, with $K = 0.1$ and $C = 1000$ (in SI units) implies $\omega_s > 1$ rad/sec for $r = 1$ mm; for 1 cm meteoroids the necessary spin rate is even lower. At the other end of the scale the Y-R effect would be insignificant if $\omega_s$ were so large that $\Delta T$ (equation 4) were very small; this would require $\omega_s > 10^3$ rad/sec, and in any case at such a spin rate the meteoroids would be unstable against ‘rotational bursting’ (Ratcliffe et al., 1980).

4. Results for the Geminids

The procedure followed here was to numerically integrate a test meteoroid around a single orbit using elements identical to the mean elements of the Geminid stream; for more details see Olsson-Steel (1987a). Small steps in true anomaly were used, and at each point the forces due to the radiative effects were calculated, and their individual contributions to the total perturbation of the orbit were summed. This gives the perturbation over a single orbit (period ~1.6 years); to get the total orbital change over an assumed age of $10^8$ years the perturbations were simply scaled up, although in reality the orbit gradually evolves. Since the radiative forces are independent of the angular elements, precession and rotation of the line of apsides over this time-frame are not important as regards the changes in the orbital energy.

It is sufficient here to quote the effect upon the semi-major axis of the test meteoroid; the changes in all the other elements are given by Olsson-Steel (1987a). Using $r = 1$ mm the radiative effects were computed, and their individual contributions to the total perturbation of the orbit were summed. This gives the perturbation over a single orbit (period ~1.6 years); to get the total orbital change over an assumed age of $10^8$ years the perturbations were simply scaled up, although in reality the orbit gradually evolves. Since the radiative forces are independent of the angular elements, precession and rotation of the line of apsides over this time-frame are not important as regards the changes in the orbital energy.

$$\Delta a = \omega \Delta T$$

Thus the total orbital shrinkage (due to RP + P-R) would be 0.12 AU, with a spread (due to Y-R) of 0.13 AU; prograde spin ($\zeta = 45^\circ$) results in a plus sign, and henceforth the shrinkage and the spread can be estimated. As an example, consider equal shrinkage and spread with $A = 0.1$ and $F = 1$; Fig. 1 shows that one would need to have $\omega_s = 1.8 \times 10^4$ rad/sec; however if the spread were three times the shrinkage then $\omega_s$ would need to be $(3)^2 = 9$ times lower, or $\omega_s = 2.000$ rad/sec.

5. Summary

It appears that the Yarkovsky-Radzievskii effect is able to accommodate the observed characteristics of the Geminid shower (reviewed by Porubcan, 1978), and is the major agent causing gradual dispersal (as opposed to gross scattering in close planetary encounters of meteoroid streams); its influence and what spin rates (or spin-up efficiency factors) of such bodies. Particular refinements which need to be included in the radiative perturbation model include:

(i) The effect of gradual spin-up after meteoroid release from the parent body;
(ii) Precession of the spin axis due to the solar radiation-imposed torque;

(iii) Integration of the test meteoroids over many orbits so that the effects of orbital evolution are incorporated;

(iv) The effect of the finite formation-time of the stream: the present model assumes all meteoroids to have been released by the parent at the same time.

In order to realistically follow the stream evolution over centuries and millennia the radiative perturbation model would need to be interfaced with models which consider ejection velocities from the parent, secular perturbations of the orbits, and possibly also the differential gravitational perturbations which depend upon the starting position in the orbit, such as the models developed by Fox et al. (1983), Jones (1985), and Jones and Hawkes (1986).

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Fig. 1. Geminid meteoroid spin rates required in order to get a spread in orbital energies (due to the Y-R effect) equal in magnitude to the perturbing forces (ΔE = F Δt), as a function of thermal inertia (units J/m²/sec²/K) for various albedoes. The plot is independent of particle size. Also shown are the thermal inertias of terrestrial (close-packed) ice, silicates and iron; the thermal inertia for Geminid meteoroids is probably about 100 - 500 J/m²/sec²/K.

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DISCUSSION

Erifo: With respect to your remark concerning rotations induced by gas drag, I just wish to mention that simple estimates of Brownian rotations of small grains in conditions appropriate to cometary ejections near 1 AU from the Sun indicate angular rotations pretty high. I tentatively suggest 10^7 radians/second for mm size. Does that fit with your concepts?
Olsson-Steel: Thank you for making this point. This is very useful to know, because until now I had been worried that if the meteoroids initially had very low spin rates, then the initial dispersion would be huge and hence predict much larger variations in orbital energies than are actually observed.
Baradzhanyo: How does the Yorkovski-Radzivelevski effect produce a mass segregation of meteoroid streams?

Olsson-Steel: It is not just the Y-R effect which is acting: I believe that largely it is the P-R (Poynting-Robertson) effect which causes the mass segregation, with the Y-R effect causing a dispersal of orbital energies about the mean orbital shrinkage (for a particular size meteoroid) due to the P-R effect. Note that this could have cosmogenic significance: in the early solar system, when the solar flux was much higher (T-Tauri stage), particles would have suffered much quicker orbital decay due to P-R effect. However, the orbital decay of prograde-spinning particles would be much lower (due to Y-R) than for similar retrograde-spinning particles, for which the Y-R and P-R effects would combine to cause much faster inspiralling. Thus, the remnant particles would mainly have prograde spin, and this may be a partial explanation of why the planets generally spin in this direction also.
Meteor stream membership criteria used in evaluating potential associations between individual meteor orbits and the mean orbit of a stream are discussed on the basis of precise photographic orbits of some meteor streams (the Taurids, Geminids, and Perseids). Serious shortcomings of the D-criterion are disclosed and suggestions on a more relevant use of the criteria for estimating stream memberships are presented, with attention paid to the distributions of the orbital elements of the streams.

Application of the D-criterion

The Southworth-Hawkins' discriminant D is defined by a combination of suitably chosen and weighted differences between the elements of two orbits, A and B, in a four-dimensional coordinate system, consisting of the differences $\Delta e = e_A - e_B$ and $\Delta q = q_A - q_B$, of the angle I between the orbital planes and of the difference $\Pi$ between the longitudes of perihelion measured from the intersection of the orbits. The value of the discriminant D is calculated from the expression:

$$D^2 = (\Delta e)^2 + (\Delta q)^2 + [2\sin(I/2)]^2 + [(e_A + e_B) + \sin(\Pi/2)]^2.$$  

The angle I and the difference $\Pi$ is given by the equations:

$$[2\sin(I/2)]^2 = [2\sin(\Delta I/2)]^2, \sin i_A \sin i_B,$$

and

$$\Pi = \omega + 2 \arcsin \left[ \cos \left( \frac{i_A + i_B}{2} \right) \sin(\Delta /2) \right], \sec(\Pi/2),$$

where $\Delta I = i_A - i_B$, $\omega = \omega_A - \omega_B$, and $\Delta i = i_A - i_B$, while the signs (+) and (-) hold for $|\Delta i| < 180^\circ$ and $|\Delta i| > 180^\circ$, respectively.

At the stream search serious intrinsic problem of the discriminant D arises from the fact that the difference between any one of the elements of two orbits which are to be compared enters only into the overall combination of the differences between all other elements, i.e. into the total value of D. Since the rejecting procedure is only based on the D-values themselves, totally neglecting actual distributions of the orbital elements in the searched meteor stream, some of the actual members of the stream can be rejected if most elements have large, though plausible deviations from the mean orbit. On the other hand, a meteor can be included into the stream while not being its actual member, if most of the orbital elements of the meteor do not differ too much from the mean orbit though one or two elements differ substantially from it.

To demonstrate this problem in an acute way we can use the orbital data on the Taurid stream, which is exceptionally diffuse. At the investigation of the stream it appeared that some of the meteors designated in the catalogues of photographic meteor orbits as the Taurids cannot be recognized as such because of very large deviations from the mean orbit of the Taurids at the corresponding solar longitude at least in one of the orbital elements (Porubčan and Stohl, 1987a and 1987b). As a typical example of this kind the meteor No. 9311 from the catalogue by Posen and McCorquodale (1967) can be given, which has been designated as the Northern Taurid. Its inclination is $i = 10^\circ 9$, which is much higher than the mean inclination of the Northern Taurids, which is $i = 320^\circ$ as derived from 42 most precise orbits of the Taurids. At the same time the differences of other
Table 1
Orbital elements and their dispersions for the Northern and Southern Taurids

<table>
<thead>
<tr>
<th>Element</th>
<th>N Taurids</th>
<th>S Taurids</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.828 ± 0.051</td>
<td>0.814 ± 0.048</td>
</tr>
<tr>
<td>q</td>
<td>0.367 ± 0.096</td>
<td>0.366 ± 0.090</td>
</tr>
<tr>
<td>E</td>
<td>292.86 ± 12.92</td>
<td>114.23 ± 11.23</td>
</tr>
<tr>
<td>T</td>
<td>228.87 ± 21.71</td>
<td>3564 ± 21.71</td>
</tr>
<tr>
<td>i</td>
<td>320 ± 121</td>
<td>575 ± 121</td>
</tr>
</tbody>
</table>

Elements with the exception of \( \lambda \) are very small: \( \Delta e = 0.029 \), \( \Delta q = 0.005 \), \( \Delta w = 198 \) (for the mean values of the orbital elements of the Taurids cf. Table 1). The D-value of its orbit is relatively high, but as a closer inspection reveals, substantial part of the value \( D^2 = 0.86 \) is caused by the difference in the ascending node \( \Delta \lambda = 28.8 \) (which equals to 1.33 \( \sigma_\lambda \)), and not in the inclination (which amounts to 0.716%).

It is evident that the D-value by itself is not an unambiguous tool for deciding about the membership of a particular meteor to a given meteor stream. At our investigation of the Taurids 10 out of the 158 meteors classified as the Northern or Southern Taurids in the catalogues of the precise photographic orbits had to be rejected not due to their large D-values, but on the basis of an extremely large deviation from the mean orbit in at least one of the elements \( e \), \( q \) or \( i \) (Porubčan and Stohl, 1987b).

Let us note that the rejection level, i.e. the maximum value of the discriminant \( D_{\text{max}} \) is usually taken the same for all searched streams and associations, depending only on the number of meteors in the investigated sample. Southworth and Hawkins (1963) adopted the value \( D_{\text{max}} = 0.20 \) for their sample of 360 orbits, with the \( D_{\text{max}} \) - value depending on the fourth root of the sample size. Lindblad (1971b) takes a more strict value \( D_{\text{max}} = 0.16 \), which can be demonstrated, however, that the actual distribution of the D-values of the members of a stream depends strongly on the concentration of the particular stream (cf. e.g. Fig. 1 in Porubčan, 1968). At such a diffuse stream as the Taurids are even the value \( D > 0.4 \) is not exceptional. In the original sample of the 158 meteors classified as Taurids 24 orbits (i.e. 15.2%) have the value \( D > 0.4 \), while the mean values of \( D \) are:

\[ D_{\text{N}} = 0.227 ± 0.178 \] for the Northern Taurids

\[ D_{\text{S}} = 0.217 ± 0.133 \] for the Southern Taurids

Even when we exclude the 10 meteors with large deviations \( \Delta e \), \( \Delta q \) or \( \Delta i \), and also another 10 meteors with their aphelion \( Q > 5.1 \) (Porubčan and Stohl, 1997b), still the mean values of \( D \) for the remaining 42 Northern and 96 Southern Taurids are \( D_{\text{N}} = 0.195 ± 0.157 \) and \( D_{\text{S}} = 0.194 ± 0.117 \), respectively; total number of orbits with \( D > 0.4 \) from this sample is 13, i.e. 9.4%.

The other intrinsic problem of the D-criterion, which consists in its inability to recognize a real member of a stream if the calculated value of the discriminant \( D \) is too large, seems to be less obvious. In a previous paper one of the authors has pointed out to the fact revealed by the examination of the frequency distributions of the orbits that many a meteor classified as sporadic one appears to be in fact members of the examined stream of the Taurids (Porubčan, 1968).

To show how a real member of a stream can be rejected by a usual procedure of the D-criterion, let us return again to the Taurids. The mean elements, derived from the most precise orbits of the Northern and Southern Taurids (42 and 96 orbits, respectively), together with their standard deviations are shown in Table 1. (We should note that in our previous list of the mean elements of a larger sample of the Taurid orbits, given in Table 2 of the paper by Porubčan and Stohl, 1987a, an inevitable error occurred in \( \lambda \); the proper values should read 219.22 for the Taurids and 3627 for the Southern Taurids). The orbits with the elements, say, \( e = e ± \sigma_e \), \( q = q ± \sigma_q \), etc., which should be considered as unambiguously belonging to the stream, have the D-values of about \( D < 0.5 \). For the orbits with \( e = e ± 2\sigma_e \), \( q = q ± 2\sigma_q \), etc., still apparently belonging to the stream, extremely high values \( D > 0.8 \) (Fig. 1).
are obtained. It should be emphasized that for these high values of the discriminant D the angular elements $\omega$ and $\lambda$ are responsible in a dominant way. If we accept, e.g., the values of the deviations in the eccentricity, perihelion and inclination to be equal to zero ($\Delta e = \Delta q = \Delta \lambda = 0$), then even the deviations $\Delta \omega = 2\delta_2$ and $\Delta \lambda = 2\delta_3$ alone are large enough to lead to the value $D = 0.5$, while the deviations $\Delta \omega = 2\delta_2$ and $\Delta \lambda = 2\delta_3$ alone give $D = 0.9$. Orbits with such high values of D would be excluded from the stream membership at the usual procedure.

The dominant role of the angular elements in the D-values at the orbits of the very diffuse and enduring Taurid stream is what could be expected from the discriminant D as it is defined. In addition to usual procedure of applying the D-criterion careful investigation of the distribution of the orbital elements, together with a more balanced weighting of their components in the D-value appears to be necessary.

Problem of weighting the D-components

In his modification of the discriminant D Drummond (1981) introduced a revised discriminant $D^*$ which utilizes a particular set of weights to render each of the elements into natural, dimensionless units, with each component making an approximately equal contribution to $D^*$, which is not the case at D, as we have seen. Drummond's discriminant $D^*$ is given by the formula:

$$D^* = \left( \Delta e / (e_0 + e_0) \right)^2 + \left( \Delta q / (q_0 + q_0) \right)^2 + \left( \Delta \lambda / (\lambda_0 + \lambda_0) \right)^2,$$

where

$$I = \arccos (\cos \alpha_1 \cos \beta_1 + \sin \alpha_1 \sin \beta_1 \cos \Delta_1),$$

$$\Theta = \arccos (\sin \alpha_1 \sin \beta_1 + \cos \alpha_1 \cos \beta_1 \sin \Delta_1),$$

with the ecliptic coordinates of the perihelion point:

$$\lambda' = \lambda + \arctg (\cos \lambda \sin \omega),$$

$$\lambda'' = \lambda + \arctg (\cos \lambda \sin \omega) + 180^\circ,$$

$$\beta' = \arcsin (\sin \lambda \sin \mu).$$

In average, the relation between D and $D^*$ is roughly linear, with the values $D = 0.250$ and $D^* = 0.105$ corresponding to each other (cf. Fig. 1 in the Drummond's paper). From the point of view of the problems with the discriminant D it is of special interest to see to what degree its shortcomings can be suppressed if the discriminant $D^*$ is used instead of D.

Figure 1 shows the relations between D and $D^*$ for the Northern and Southern Taurids, Geminids and Perseids. It includes also the photometric orbits from less precise catalogue by McCrosky and Posen (1961), where the orbits had been derived by graphical method. It is seen that the relation for streams with low inclination (the Taurids, Geminids) is very loose, which was to be expected. At these showers several orbits with very large values of D do not correspond to the orbits with the largest values of $D^*$ and vice versa. Inspection of these cases can be revealing to the actual relation between the discriminants D and $D^*$, and also on the weighting problem.

As an example of this kind we can take the Southern Taurid No. 11912 with the largest value of $D^* = 0.404$. While get the discriminant D two thirds of the $D^*$-value go to the fourth component which represents a weighted function of the difference between the longitudes of perihelion, at the discriminant $D^*$ the element $q$ is almost entirely responsible for 88% of the $D^*$-value, though the deviation $\Delta q = 0.190$ only slightly exceeds $2\delta_2$ and the deviations of the angular elements are $\Delta \omega = 215^\circ$ (which equals to 1.96$\delta_2$) and $\Delta \lambda = 49^\circ$ (which equals to 2$\delta_3$). Overemphasis on the deviations $\Delta q$ at the discriminant $D^*$ is evident in this case, as it is also in many other cases, The Southern Taurid No. 12189, e.g., has an extremely large deviation in the inclination of its orbit, $\Delta i = 1670^\circ$ (which equals to $14.5^\circ$! ), but still for 49% of the $D^2$-value the element $q$ is responsible, the prohibitive deviation $\Delta i$ being almost neglected in the $D^2$-value.

Among the Geminids (Fig. 1c) at both the orbits with the two largest values of $D^* (0.178$ and 0.171) the element $q$ is almost entirely responsible for these values, with the remaining components adding to the $D^2$-values 98% and 96%, respectively.

On the other hand, in the case of the largest $D^*$-value among the meteors of the high-inclined stream of the Perseids, the effect of $q$ on the $D^*$-value is completely negligible with 91% of $D^2$ coming from the difference in the eccentricity, $\Delta e = 0.365$.

A need to distinguish between various showers at the weighting of both the D- and $D^*$-components seems to be obvious, and a more thorough analysis of different showers is inevitable for estimation of any proper weights.

A note should be added about the inefficiency of the discriminants D and $D^*$ to solve unambiguously the question of the membership of a particular meteor orbit to a shower. Orbits of the meteors classified as Taurids in the photographic catalogues, but removed from our list of the Taurids because of large deviations in their elements, e. g. or i, do not have the largest values of $D^*$, in the case of the meteor No. 4670, classified in the catalogues as the Southern Taurid, the $D^*$-value is as low as $D^* = 0.139$, not leaving any doubt on its membership to the stream. Still, its difference $\Delta i = 10^\circ$ in the inclination (which equals to $0.6^\circ$) shows clearly that the meteor cannot be taken as a real member of the Taurid stream.

In general it is possible to state that the discriminant $D^*$, though perhaps with a better weighting of the $D^*$-value components, still does not solve the problem of the short-cuts of the stream membership criterion because of its neglecting the actual dispersion of the orbital elements. On a possible way how to include the dispersions of the orbital elements into the stream membership criterion has been pointed out by one of the authors with his S-criterion (Forbush, 1977).

The D-criterion based on the varied mean orbit

At the streams of a short duration, not exceeding a few days, it is usually sufficient to represent their orbit by the mean orbital elements, unvaried in the course of the streams activity. The mean orbit, however, is not sufficient at the streams with their activity extending over several weeks or months. The $D$-values of meteor orbits calculated with respect to the mean orbit of
such a long-enduring stream cannot give relevant information about the membership, especially of those meteors which are at the outskirts of the stream.

On Fig. 2 the D-values versus the solar longitude L⊙ are plotted for the Taurid stream extending its activity over more than four months. Systematic change of the D-values calculated with respect of the mean orbits of the Northern or Southern Taurids presented in Table 1 is evident (Fig. 2, upper part). The lower part of Fig. 2 shows clearly to what degree the D-values are reduced, if calculated with respect to the varied mean orbit which takes into account systematic change of the orbital elements in the course of the streams activity (for the values of the varied mean orbit cf. Porubčan and Stohl, 1987b). The mean value of D calculated with respect to the varied mean orbits is $D_{\text{var}} = 0.124 \pm 0.099$ for the 42 precise orbits of the Northern Taurids and $D_{\text{var}} = 0.101 \pm 0.068$ for the 96 precise orbits of the Southern Taurids, as compared with the corresponding values $D_{\text{nor}} = 0.195 \pm 0.157$ and $D_{\text{nor}} = 0.194 \pm 0.117$ derived with respect to the mean orbits, as given above.

At any search for associations between meteor streams and/or their potential parent objects it is necessary to apply the D-criterion with respect to the varied mean orbit, if the association should not be underestimated (cf. Porubčan and Stohl, 1987b, for the associations of some minor streams with the Taurid stream).

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The aim of this paper was to present some more serious problems and shortcomings of the usual application of the D-criterion. A new method of weighting the D-value components with attention paid to the dispersions of the orbital elements appears to be necessary, though its formulation is outside the scope of the present paper.

It should be emphasized once more that a careful use of the D-criterion is strongly recommended when it is applied to the orbits at the search of potential associations. Its shortcomings shown above should be taken into account to avoid both the underestimation and overestimation of the associations.

One important note should be added. While the D-criterion can be a very useful tool in statistical studies of the streams present in a large sample of the orbits, end to some degree also in finding the associations between various streams and objects, its application to the genetic relations must be taken with a reservation. As was pointed out by Drummond (1981) and stressed by Babadzhanov and Obrubov (1983), application of the relationship criteria to the present-state orbits neglects important fact that because of the perturbations and orbital evolution, the orbits which are very similar at present could differ very much in the past. Even a low calculated value of the discriminant D (or any other discriminant) does not necessarily confirm the filliation between a meteor stream and a comet or an asteroid.
The Taurid meteor complex associated with P/Encke is studied on the basis of relevant photographic and radar orbits. Orbital characteristics, radiants and durations of the preperihelion showers are compared with corresponding theoretical values derived from the observations of the preperihelion Taurids. Reality of the proposed associations of minor showers with the Taurid complex and the total duration of its activity are evaluated and discussed. Some of the associated showers (the Northern and Southern X Orionids, Northern Piscids and Southern Arietids) are confirmed to be in fact parts of the Taurid shower itself.

Introduction

From the point of view of the evolution and equilibrium of the whole meteoric complex in the inner part of the solar system the study of the showers and bodies associated with the short-period comet P/Encke is of a special interest (Whipple, 1967 and 1976; Delome, 1976; Kresák, 1980; Napier, 1983; Clube and Napier, 1986 etc.) All these showers comprise a very dispersed and rich complex which, because of its very low inclination, is met by the Earth twice a year, both at the preperihelion and postperihelion encounters.

With different degree of assurance it is possible to include into the complex about ten meteor showers (Sekanina, 1973 and 1976; Drummond, 1981) a very diffuse stream of sporadic meteors (Stohl, 1986), some larger meteoric bodies, and also a few Apollo asteroids (Clube and Napier, 1986; Olsinn-Steele, 1987). The most significant representative of the complex is the Taurid shower, consisting of the Northern and Southern branches, observed in the nighttime hours at the preperihelion encounter, with its duration extending over three months. At the postperihelion encounter the complex is observed as the daytime Taurids, of considerably shorter duration (about two weeks according to Cook, 1973, and about one month according to Sekanina, 1976).

Because of the very large spread, long duration and complex structure of the Taurid stream, associations of various showers and objects calculated relative to the "mean orbit" of this stream (or of its branches) might lead to ambiguous results and need a reexamination. The aim of the present paper is to investigate in more detailed observed characteristics of the stream and to evaluate the associations and the extension of the whole complex.

Orbits and radiants of the Taurid stream

Most precise orbits of meteors are provided by photographic observations which, however, are bound to the nighttime period yielding thus only data from the preperihelion encounter of the Taurid stream with the Earth. At the postperihelion encounter the geocentric radiants of the stream are concentrated in an area close to the Sun, producing thus daytime meteors which can only be observed by the radio technique.

As was demonstrated in a previous paper analyzing photographic orbits (Porubčan and Stohl, 1987), the mean orbit of the Taurids varies considerably in the course of the stream's enduring activity. The varied mean orbit of the Taurids given in the previous paper was derived for the stream as a whole. It was justified by the fact that the intrinsic dispersion of the orbits within each of the two branches was much larger than the difference between their mean orbits and that with the exception of the inclination and orientation the orbits of the Northern and Southern Taurids were practically identical (cf. Table 2 in Porubčan and Stohl, 1987). More rigorous investigation of the shower, including radiants of all its individual members reveals, however, that both the branches are in fact clearly distinct.

The varied mean orbits were therefore again derived, separately for the Northern and Southern branches of the stream. From the whole set of 138 orbits listed in the catalogues as the Northern or Southern Taurids (Porubčan, 1978; Porubčan and Stohl, 1987) 10 orbits had to be excluded due to their wrong original classification as the Taurids, which was revealed by a thorough inspection of the distribution of individual orbital elements (Nos. 2263, 2473 and 2630 by Whipple, 1954; No. 3886 by Jacchia and Whipple, 1961; Nos. 9311, 12114 and 12189 by Pose and McCrosky, 1967; Nos. 4670 and 5298 by Hawkins and Southworth, 1961; No. 71942 by Babadzhanov et al., 1968). In the present investigation we have excluded further 10 orbits with aphelia beyond the orbit of Jupiter (in the range from 5.5 to 7.3 AU), which might misrepresent the stream's original orbit (Nos. 1526, 1893 and 2957 by Whipple, 1954; No. 5511 by Jacchia and Whipple, 1961; Nos. 9504, 11037, 11208 and 12064 by Pose and McCrosky, 1967; Nos. 4670 and 5298 by Hawkins and Southworth, 1961; No. 71942 by Babadzhanov et al., 1968).

Fig. 1. Orbits of the 138 photographic Taurids projected into the plane of the ecliptic (J, E - orbits of Jupiter and Earth).
The solar longitude 220° taken as the reference ordinates; it is presented in Table 2 again with been therefore derived rather in the ecliptical coordinates. The mean daily motion of the radiants has radiants as a linear function of the equatorial coordinates of individual meteors and other shower associated in Table 1 both for the Northern and Southern Taurids. As the reference solar longitude the value of 220° was chosen, which is close to the maximum of the shower's activity. These varied mean orbits should be referred to when evaluating possible associations of meteoric and other showers with the Taurids. Geocentric radiants of 106 Taurids (30 Northern and 76 Southern Taurids) listed in the photographic catalogues have been used for the calculation of the daily motion of their radiants. It is evident that because of the long duration of this stream it is meaningless to express the daily motion of their radiants. It is evident that only a relatively small part of the night Taurid meteors observed at the preperihelion passage can intersect the orbit of the Earth at both nodes (cf. the last plot of Fig. 2) and only these could be observed at the postperihelion passage as the daytime shower. There are altogether 10 orbits only (4 N Taurids and 6 S Taurids) out of the complete set of the 138 orbits, which have both their nodes close enough to the Earth's orbit to be observed. All these orbits correspond to the meteoric and other showers observed at the end of the Taurids activity, in between the solar longitudes 200° - 230°. The equatorial coordinates of the expected daytime radiants corresponding to the mean orbits of this sample, computed separately for the 4 Northern and the 6 Southern Taurids are given in the first two rows of Table 3. The daytime showers associated with the nighttime Taurid shower, i.e. the β Taurids and the β Perseids.

Fig. 2. Distribution of the nodes of the Taurids in the plane of the ecliptic (heavy arcs - the preperihelion nodes; dots - the postperihelion nodes which the meteoroids collide with the preperihelion period lies exactly on the Earth's orbit. The positions of the other corresponding nodes are defined by intersection of the lines of nodes with the ecliptic and can be found from the orbital elements a, e and ω. The distribution of both the nodes of 138 photographic orbits of the Taurids is shown in Fig. 2. The preperihelion nodes are denoted by the heavy arcs on the circular orbit of the Earth, which at the same time delineate the periods of the Taurids activity for the corresponding solar longitudes, indicated by the numbers above each circle. The postperihelion nodes are marked by dots. In the upper left plot the complete set of the nodes from the whole period of the Taurids activity is presented, while the following three plots depict the distribution of the nodes in three different periods of the stream's activity, around the core of the stream (210° < L < 230°) and at both its wings (170° < L < 190°, 230° < L < 270°).

The plots indicate that the mean radius vector of the postperihelion nodes of the Taurids increases systematically with the solar longitude; this increase is identical both for the Northern and Southern Taurids. It is evident that only a relatively small part of the night Taurid meteors observed at the preperihelion passage can intersect the orbit of the Earth at both nodes (cf. the last plot of Fig. 2) and only these could be observed also at the postperihelion passage as the daytime shower. There are altogether 10 orbits only (4 N Taurids and 6 S Taurids) out of the complete set of the 138 orbits, which have both their nodes close enough to the Earth's orbit to be observed. All these orbits correspond to the meteoric and other showers observed at the end of the Taurids activity, in between the solar longitudes 200° - 230°. The equatorial coordinates of the expected daytime radiants corresponding to the mean orbits of this sample, computed separately for the 4 Northern and the 6 Southern Taurids are given in the first two rows of Table 3. The daytime showers associated with the nighttime Taurid shower, i.e. the β Taurids and the β Perseids.

Table 1

| Northern Taurids: | a = 2.15 + 0.0069 L_e | e = 0.336 + 0.0066 L_e | q = 0.347 + 0.0024 L_e | i = 39°8 - 0°93 L_e | ω = 29°29 - 0°34 L_e | ω = 154°9 + 0°26 L_e |
| Southern Taurids: | a = 2.05 + 0.0063 L_e | e = 0.511 - 0.0063 L_e | q = 0.381 + 0.0010 L_e | i = 41°32 - 0°014 L_e | ω = 111°6 - 0°242 L_e | ω = 150°6 + 0°38 L_e |

Table 2

| Northern Taurids: | λ = 52°6 + 0°389 L_e | β = 276° - 0°001 L_e |
| Southern Taurids: | λ = 51°1 + 0°582 L_e | β = -51° - 0°02 L_e |
revealed by radio observations after the theoretical prediction by Whipple (1940), have their geocentric radiants very different from the expected one (cf. in Table 3 the corresponding values, as derived by various authors). Though the period of the activity of the expected daytime Taurids coincides with that of the Perseids, the radiants are distinctly different, especially in the right ascension. It can be concluded that the derived daytime appearance of the Taurids cannot be looked upon just as the extensions of the known Taurids and Perseids and that these two showers should be considered as distinct branches of the Taurid complex.

Evaluation of tentative associations

The increase of the radius vector of the Taurids postperihelion nodes with the solar longitude reflects the fact that the size and orientation of the mean Taurid orbit is dependent on the solar longitude (cf. Fig. 3 in Porubcan and Stohl, 1987), which is also evident from the variations of the orbital elements (Table 1). Let us verify to what degree the streams for which associations with the Taurids have been proposed do agree with the derived varied mean orbits of the Taurids, as are presented in Table 1. At the preperihelion encounter the tentatively associated streams include: the Southern Arietids, Northern Piscideas, Northern and Southern Orionids, Geminids and Canids, while the postperihelion complex includes the Taurids, Perseids and Geminids and Canids (Sekanina, 1973 and 1976; Cook, 1973). In Figure 3 the positions of the nodes of the mean orbits of the showers are shown. The preperihelion orbits have the nodes designated by open circles connected by full lines, and the nodes of the postperihelion orbits are marked as crosses connected by dashed lines. The full circles mark the nodes of the Taurid mean orbits for five intervals of the solar longitude, each of 20° wide (170° - 190°, 190° - 210°, etc.). The change of the radius vector of the postperihelion Taurid nodes with Lₜ is evident. The Taurids are observed at the solar longitude, at which the mean postperihelion Taurid node should intersect the Earth's orbit, taking into account the systematic change of the nodes. It is likely that the Geminids and Canids follow progression of the Taurid postperihelion node, too. The postperihelion node of the Geminids is close to the orbit of the Earth and, consequently, they should be observed also as a daytime shower, with the expected coordinates of the theoretical radiant αₜ = 109°, δₜ = +13° at Lₜ = 107°, while the descending node of the Canids is too far from the Earth to be observed.

As can be seen in Fig.3, the nodes of the Orionids are practically identical with the nodes of the last Taurid period (250° < Lₜ < 270°). In his list of meteor showers Cook (1973) distinguishes two branches of the Orionids, i.e. the Northern and Southern Orionids. A comparison of their orbits and radiants with the mean orbits and radiants of the Northern and Southern Taurids corresponding to the same period has revealed that the Northern branches on the one hand and the Southern branches on the other hand of both these showers are identical. We thus can conclude that the Orionids are in fact regular parts of the Taurids. The same conclusion holds true also for the Southern Arietids, which are in fact regular parts of the Southern Taurids, and with a less certainty also for the Northern Piscideas, which seem to be regular part of the Northern Taurids.

### Table 3

<table>
<thead>
<tr>
<th>Shower</th>
<th>αG</th>
<th>δG</th>
<th>Lₜ</th>
<th>Duration</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>N Taurids (C):</td>
<td>76°</td>
<td>+21°</td>
<td>77°</td>
<td>-20°</td>
<td>present paper</td>
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<tr>
<td>S Taurids (C):</td>
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<td>+30°</td>
<td>77°</td>
<td>-20°</td>
<td>present paper</td>
</tr>
<tr>
<td>β Taurids (C):</td>
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<td>+19°</td>
<td>96°</td>
<td>13</td>
<td>Cook (1973)</td>
</tr>
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<td>Geminids (C):</td>
<td>80°</td>
<td>+21°</td>
<td>94°</td>
<td>24</td>
<td>Sekanina (1973)</td>
</tr>
<tr>
<td>Canids (C):</td>
<td>84°</td>
<td>+27°</td>
<td>98°</td>
<td>14</td>
<td>Sekanina (1976)</td>
</tr>
</tbody>
</table>

(C - calculated, O - observed)

### Table 4

The geocentric radiants of the showers which should be considered as regular parts of the Taurids, with the corresponding radiants of the Northern (N) or Southern (S) Taurids.

<table>
<thead>
<tr>
<th>Shower</th>
<th>αG</th>
<th>δG</th>
<th>Ref.</th>
<th>Lₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>S Arietids</td>
<td>24°</td>
<td>+9°</td>
<td>a</td>
<td>180°</td>
</tr>
<tr>
<td>S Taurids</td>
<td>25°</td>
<td>+5°</td>
<td>c</td>
<td>188°</td>
</tr>
<tr>
<td>N Piscids</td>
<td>26°</td>
<td>14°</td>
<td>b</td>
<td>199°</td>
</tr>
<tr>
<td>N Taurids</td>
<td>31°</td>
<td>+15°</td>
<td>c</td>
<td>199°</td>
</tr>
<tr>
<td>X Orionids</td>
<td>84°</td>
<td>26°</td>
<td>b</td>
<td>258°</td>
</tr>
<tr>
<td>X Orionids</td>
<td>85°</td>
<td>16°</td>
<td>b</td>
<td>259°</td>
</tr>
<tr>
<td>S Taurids</td>
<td>83°</td>
<td>+17°</td>
<td>c</td>
<td>239°</td>
</tr>
</tbody>
</table>

Ref.: a - Sekanina (1973); b - Cook (1973); c - present paper.
The positions of the geocentric radiants and of the elements of the mean orbits of all these pre-perihelion showers are presented in Tables 4 and 5, together with the corresponding values for the Northern and Southern Taurids, derived by the extrapolation of their radiants daily motion (Table 2) and of their varied mean orbits (Table 1). The values of the Southworth-Hawkins $D$-criterion (Southworth and Hawkins, 1954), calculated for the minor showers orbits with respect to the corresponding varied mean orbits of the Northern or Southern Taurids, are given in the last column of Table 5. It is seen that the $D$-values are in general very low, confirming very close relation of these showers to the Taurids. For comparison it can be noted that the mean values of the $D$-criterion of all precise individual orbits of the Taurids calculated with respect to their varied mean orbits are 0.141 and 0.116 for the Northern and Southern Taurids, respectively. The association of the Geminids ($D = 0.163$) and Canids ($D = 0.205$) is not so obvious, while the association of the $\delta$-Serenids ($D = 0.715$) remains highly spurious.

Conclusions

The orbital elements of the Northern and Southern Taurids, derived from the precise photographic data confirm that the pre-perihelion activity of the Taurid complex associated with $\delta$-Encke extends over a period of the solar longitudes of about 180°-200°, from the first half of September till the second half of January, i.e. between the solar longitudes of about 170°-300°. The minor showers of the Southern Arietids (Southern Piscids), Northern and Southern $\xi$-Orionids and possibly $\xi$-Cygni should be considered as regular parts of the Taurid shower.

Investigation of the post-perihelion activity of the Taurid complex confirms systematic increase of the mean radius vector of its post-perihelion nodes; the $\beta$ Taurids and $\xi$-Perseids do not correspond to the expected positions of the nodes, radiants and orbits of the Taurids and should be therefore considered as another branches of the complex.

Large spread of the orbits and very long duration of the activity of the Taurid complex make it difficult to explain in a simple way the process of its origin and evolution. The present value of the longitude of perihelion of its parent comet P/Encke is $\lambda = 160^\circ$, while the spread of the longitudes of perihelia of the whole complex extends from the value $\lambda = 115^\circ$ up to $\lambda = 190^\circ$. Since the longitude of perihelion of P/Encke increases with time (with a complete period of more than 50 000 years), large part of the Taurid complex is with their $\lambda$-values much ahead of the comet, which is hardly possible to explain by a diffusing process of the stream. Very large age of the Taurid complex (> 10$^5$ years) seems to be plausible from this point of view, though the definite solution can be expected only from very precise calculations of long-term evolution of the orbits of the whole complex.

REFERENCES


<table>
<thead>
<tr>
<th>Shower</th>
<th>a</th>
<th>e</th>
<th>i</th>
<th>$\omega$</th>
<th>$\lambda$</th>
<th>$\pi$</th>
<th>Ref.</th>
<th>$L_\theta$</th>
<th>D</th>
</tr>
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<td>S Ari</td>
<td>1.723</td>
<td>0.841</td>
<td>17.4</td>
<td>126.9</td>
<td>7.8</td>
<td>134.7</td>
<td>a</td>
<td></td>
<td></td>
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<tr>
<td>S Tau</td>
<td>1.77</td>
<td>0.871</td>
<td>5.8</td>
<td>126</td>
<td>8</td>
<td>132</td>
<td>c</td>
<td>188°</td>
<td>0.082</td>
</tr>
<tr>
<td>N Pis</td>
<td>2.06</td>
<td>0.80</td>
<td>3</td>
<td>291</td>
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<td>130</td>
<td>b</td>
<td></td>
<td></td>
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<tr>
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<td>0.850</td>
<td>3.8</td>
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<td>N XOr</td>
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<td>2</td>
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<td>79</td>
<td>175</td>
<td>c</td>
<td>259</td>
<td>0.087</td>
</tr>
</tbody>
</table>
Olsson-Staël: This is a very important complex of material since it seems to be the major source of the zodiacal dust cloud. Apart from P/Encke, the Taurid complex includes several Apollo asteroids and also perhaps a long period comet (1967 II Rudnicki).

Stohl: I absolutely agree that the complex is very important, as it is stressed in the introduction of the paper (not read at the session). One should be, however, careful in accepting the associations derived by using the D-criterion, as it is shown in another paper by myself and Dr. Potubčan (this volume TS-2).

Babadzhanov: Your results correspond to the calculations of secular perturbations. But because of the secular variations of the orbital elements of the stream meteoroids, the value of the D-criterion also changes and sometimes becomes too large. This must be taken into account.

Stohl: I completely agree that the evolutionary change of the D-value must be taken into account, but the results of the evolution of the orbital elements as derived by various authors are entirely discordant. At present it is therefore impossible to explain the origin of the whole Taurid complex in a unique way.
Mechanisms leading to higher particle concentrations in several places along the meteor stream associated with comet Halley are discussed. The positions of the mass concentrations represented by the mean anomaly of the stream orbit, as determined from long series of observations of the Orionids and Eta Aquarids, are correlated with the deviations in the semi-major axis and nodes of the evolving orbit of the comet. It is shown that random deviations in the orbital elements of the comet may be responsible for the nonstable mass concentrations in the stream.

1. Introduction

The activity of meteor showers associated with comet Halley doesn't show any standard features. The flux of particles varies with the solar longitude, as well as in consecutive returns of showers. The structural features of the stream have been studied in detail by McIntosh and Hajduk (1983), giving satisfactory explanation for most of them within their shell model of the stream (especially for the particle distribution and variations in the stream's cross section). However, some aspects of the stream structure may be explained by mechanisms working with the different speed, as suggested by Jones and McIntosh (1986). In the present paper an explanation of the particle mass concentrations along the stream, occurring semiperiodically in the returns of the Orionid meteor shower is suggested as a possible consequence of the deviations in semi-major axis $A_a$ and nodes $\Delta\Omega$ of the orbit of the parent comet and particles ejected from it during its perihelion passages.

2. The deviation in semi-major axis

In consequence of planetary perturbations and nongravitational forces, the orbital elements of the parent comet vary in consecutive returns. The particles, produced by the comet during its perihelion passages have initial orbits close to the orbit of parent comet. Deviations in elements of the comet orbit may then cause either a larger spread, or a concentration of particle orbits. The largest influence on the particle orbits will have elements, undergoing to the largest changes in consecutive revolutions, and these are the semi-major axis $a$ and the ascending node $\Omega$, as seen from the tables of osculating elements, calculated for comet Halley by Yeomans and Kiang (1981) or by Landgraf (1986). As the elements of both sets tend to disagree for the revolutions before 240 BC, as shown by Sitarski and Ziolkowski (1986), we will take for our analysis data since 240 BC, the errors of which diminishes towards the present. In Fig. 1 there are given the values of $a$ and $\Delta a$ in astronomical units for 31 revolutions, from 240 BC to 2061, with the elements for 1986 and 2061 according to Yeomans (1977). Similarly in Fig. 2 there are given the values of $\Delta\Omega$.

The question of our present interest is, to what extent may the deviations of $A_a$ and $\Delta\Omega$ influence the distribution of particle orbits, and hence, to what extent they can cause mass concentrations along the stream (and also across it), related to the observed variations in the activity of meteor showers. As it is seen in Fig. 1 and Fig. 2, the effect of both deviations is random and there is no correlation between them. But the number distribution of both sets of data, as it is shown in Fig. 3, is concentrated about the mean values of deviations. In the same time the value of $\Delta\Omega = 1^\circ$ represents also the mean step in the gradual change of $\Omega$, at least for the time span of the considered revolutions. However, the number distribution of $\Delta a$ values alone, does not represent either the concentration of particle orbits at $\Delta\Omega = 0^\circ$, nor the largest spread at $\Delta\Omega = 2^\circ$, as these values should be projected in the direction of the orbital velocity of the comet at the point of particular nodal distance $r_\Omega$, corresponding to a given $\Omega$. The gradual change of $\Omega$ and $r_\Omega$ with the revolutions of the comet is caused by the gradual tilt of the major axis and therefore is independent on the consecutive changes of $A_a$. Hence, at the Earth distance the values of $A_a/a$ and $\Delta\Omega$ in combination with $r_\Omega$ represent two different mechanisms, influencing the possible spread or concentration of particles along the whole meteor stream.

3. The evolution of particle orbits

The evolution of orbits of the meteoroid size particles, ejected from the nucleus of the comet at the different perihelion passages, has been studied by Jones and McIntosh (1986) and Babadzhanov et al. (1987). Different masses of particles or different ejection velocities have been considered. The orbital evolution of particles, especially the time required for the Earth-crossing orbits depends strongly on the position of nodes and of nodal distances of the initial orbit, because of the progressive change of these parameters with the evolving orbit of the comet. From the location of nodes for the returns of the comet and from the minimum distances between the orbits of the Earth and comet Halley (see Fig. 2 - 4 of the paper by Hajduk, 1983) it is clear, that particles released from the comet during the passages shortly before 836 BC, when the nodal dis-
The deviations of semi-major axis of comet Halley for its successive revolutions.

Fig. 1.

The deviations of \( \Omega \) between the successive orbits of comet Halley.

Fig. 2.

The activity of the Orionid meteor shower from 1910 to 1986, corresponding to the particle flux along the whole length of the stream; \( A/A_o \) - the level of activity, \( M \) - mean anomaly.

Fig. 4.
activity maxima along the stream at the position of Orionids and Eta Aquarids.

This conclusion could be verified by observations of the radiant fields of both showers: At the activity minima a relatively homogeneous dispersion of the shower meteor radiants should be observed, but at the activity maxima, when crossings of orbits with particular $e$ and $Q$ are assumed, it should be structured from two well distinguished smaller fields of radiants within the total radiant area. We may hope that the recent International Halley watch observations will be able to answer this question definitely.

REFERENCES

Critical analysis of the results of space experiments, taking into account the contribution of large particles, leads to much higher values of dust production rate than those derived from the first analysis of space measurements. As a consequence it seems necessary to correct the mass to dust ratio of the mass production by a factor of 10, from 0.1-1.0 to 1.0-10. The corrected values of dust production rate are in much better agreement both with the current concepts of the comet's history and with the evolution of its meteor stream.

1. Introduction

In spite of enormously great amount of data, gathered by the International Halley Watch net and by the space probes to comet Halley, many physical characteristics of the comet are known only within very large limits and many problems, concerning the physical processes going on on the nucleus surface remain open. There are broad discussions about the principal characteristics of the comet: its mass and density, with the estimates, differing by an order of magnitude.

Some paradoxical relations seem to occur from the different models of cometary nuclei: when taking a high density nucleus, corresponding to the chondritic material (Jessberger et al., 1986), then the measured dust:gas ratios are too low; when, on the other hand, the mass production with a low dust to gas ratios are assumed to be real, corresponding to a very low density material, then the total mass of the nucleus seems to be too small, to supply the mass of the meteoroid stream over the long orbital history of the comet, corresponding to the stability of the comet orbit.

We would like to show here, that at least one of the weak points in calculations of the characteristics of the comet is in the low dust:gas ratios used, and consequently in the low value of the comet's mass production.

2. The dust:gas ratio, the mass index and the limiting particle mass

The dust:gas ratio estimates for the comet's mass production prefer, in general, gas over dust, with values of $M_d/M_g$ between 0.1-1.0, (where $M_d$ is mass loss for a given time unit and $M_g$ gas loss, respectively). Rarely were higher values reported, with the upper limit of 2.0 (Helin and Keller, 1981). The estimates for P/Halley tend to prefer the value of 0.3 (Whipple, 1986; Krešáč, 1986). However, in a very few cases give the authors mass limits, for which these values are valid. Usually it is tacitly assumed that the estimated dust:gas ratio is valid generally, over the whole scale of particle masses. But this is exactly the weak point of such estimates. With the assumption of a general validity of the dust:gas ratio it is, in fact, assumed that the integrated mass index $S$ (defining the slope of the particle flux - mass distribution) is over the whole mass scale $S > 1$. Only this condition decreases the mass contribution of larger particles. Moreover, it is assumed that the contribution of larger particles has a cut-off at a certain mass value. But these assumptions, especially the former one, are hardly fulfilled.

The results of the space experiments show mass indices increasing towards the larger masses up to $10^{-9}$ kg, where they reach a maximum value with $S = 1$ (Mazets et al., 1986; McDonnell et al., 1986). Then, as shown from the large dust experiments and radio-metric data (McDonnell et al., 1986; Edenhofer et al., 1986; Hajduk and Kaplický, 1987) the mass index decreases again, up to the mass limit at $10^{-7}$ kg particles with $S = 0.3$. But this means, that shifting the mass range of the ejected particles from its upper limit of 1 g, as usually assumed, to 1 kg, we obtain the dust:gas ratio $M_d/M_g = 3.1$ instead of 0.3:1, as given in most considerations. This is approximately the same value as suggested by Crifo (1987), giving $M_d/M_g = 3.4$ as a most probable value, assuming contribution mostly from particles with mass $m < 10^{-1}$ kg. For the mass limit of $m < 30$ kg Crifo gives $M_d/M_g = 19$. In extraordinary cases, concerning the split comets, we do not have any mass limit for the fragments or parts of the nucleus. In any case, this means that the maximum contribution of the cometary ejecta is in the range of largest particles. This conclusion is also supported by the radar detection of large fragments of the comet IRAS-Araki-Alcock (Goldstein et al., 1984).

Naturally, with the increasing mass of particles (or bodies, respectively) decreases the particle flux by many orders of magnitude and we cannot verify these conclusions by the short-term experiments. We need here observations of particles, spread in the meteor stream over many revolutions of the comet. But the meteor observations, corresponding to particles with the mass indices $S = 1$ (Hajdukova et al., 1986) and the mass contribution of shower meteors has a maximum for particle masses at about $m = 10^{-4}$ kg (Hajduk, 1986). Hence, those observations do not confirm the presence of larger bodies in the amount, corresponding to the extrapolated values from space experiments. (E.g. if we would change $S$ from 1 to 0.9, we would obtain twice as high particle flux for the particle masses differing by 5 orders, or for meteor magnitudes differing by 7.5 mag.) This discrepancy can be explained by accepting the evolution of the mass index with the time as suggested recently (Hajduk and Kaplický, 1987) for the mass distribution of particles ejected from P/Halley. For the fresh ejecta with $S = 0.5$, corresponding to the halo particle population around the nucleus we thus have the maximum mass contribution from particles of the mass $m = 10^2$ kg. As the value of $S$ increases up to 0.8 and 1.1 for the young or old stream particles, respectively, the maximum mass contribution is shifted to $10^{-2}$ kg $M_d$ particles. Hence the most probable dust:gas ratio of the comet material should be between 1.0-10 and not between 0.1-1.0.

The change of $S$ is in agreement with the results of Šimek (1987) deduced from the observations of
five meteor showers, and it means that the cometary ejecta undergo to a permanent change in their size, excluding gradually larger bodies from the stream in course of their return to the perihelion. The effects influencing this process may be different (collisions, evaporation or combined effects), depending on the composition and structure of particles. The result of this process is the maximum contribution of particles of the intermediate masses of about $10^{-5}$-10^{-3} kg as obtained from meteor shower data, and independently from studies of the micrometer distributions (Grün, 1987).

3. The influence of the corrected dust:gas ratios on the physical parameters of the nucleus and on the orbital history of the comet

The result that the maximum contribution of the fresh cometary ejecta is in the range of largest masses, has a great influence on the calculation of the comet’s age and lifetime. The larger dust:gas ratios are in better agreement with the observations of Halley showers. The mean dust production obtained from these observations is 3.2x10^{-17} kg/rev. (McIntosh and Hajduk, 1983), referred to a long-term physical history of the comet. This value is 2 times larger than the one used by Hughes (1986) and Krasáč (1986) from the results of space experiments and ground-based observations, assuming $M_d/M_g$=0.3, and corresponding to the observational value of $M_d$=3x10^{-17} kg/s at 1 AU. Mazota et al. (1986) obtained from Vega 1 SP2 sensors a value of $M_d$=1x10^{-17} kg/s at 0.79 AU and Krasnopolsky et al. (1986) from Vega 2 obtained $M_d$=1x10^{-17} kg/s at 0.83 AU. Adapting a moderate increase of the dust:gas ratio we would agree completely with the results of meteor observations and with the required 2 300 revolutions of the comet (Hajduk, 1984; Hughes, 1985, 1986). With much higher dust:gas ratios it would be possible to shorten the orbital history of the comet.

The value of $M_d$=2.8x10^{-17} kg/rev. was used by Rickman (1986) in his calculations of the nuclear mass of P/Halley from the effects of the nongravitational forces on the orbit of the comet. He obtained for the comet’s mass $M_0$=6x10^{14} kg, which gives, with the observed size of the nucleus and its volume of 5x10^{11} m^3 a very low density in the range of 0.1 < $\rho$ < 0.2 g/cm^3. In a similar way Sagdeev, Elyasberg and Moroz (1986) determined the nucleus mass of P/Halley to $M_0$=2x10^{14} kg and density $\rho$=0.4 g/cm^3 with errors $\delta M_0$=2% and $\delta \rho$=0.05 g/cm^3, using dust:gas ratios of 0.1 < $M_d/M_g$ < 1.0. Because of the low velocity of the dust, in comparison with the gas outflow from the nucleus, the dust production is less essential for the calculation of nongravitational forces. The uncertainties arise here mostly from the $A_1$ and $A_2$ parameters, as shown by Whipple (1986). However, the dust production is very essential for the calculation of the comet’s lifetime and for its orbital history. This is connected with the spatial density of particles observed within the stream and with the total mass of the stream. The mass $M_d$=5x10^{14} kg deduced by Hughes (1985) for the nucleus of P/Halley is in the best agreement with the comet’s orbital history of about 2 300 revolutions and with the about equal future lifetime. Rickman’s value for the nuclear mass would shorten extremely the lifetime of the comet. The values of Sagdeev et al. may agree with those given by Hughes near their upper limits.

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D I S C U S S I O N

Grün: What are the biggest particles in meteor streams? Cannot these particles be taken as the biggest particles released from comets? Hajduk: The final value (corresponds to about 1 kg particles) of $M_d/M_g$ is large in grains. This limited capability has been overlooked previous to P/Halley Flyby, with most authors fitting the optical data with a dust size distribution, which arbitrarily excludes large (> 10^6 g) grains. If you perform fits of the same data with distributions, which allow for large grains, you find that an order of magnitude increase in the mass-loss rate is allowed, and therefore you come up with a large uncertainty in $M_d/M_g$.

Fechtig: The latest value for $M_d/M_g$ as discussed by Geiss is 0.5. However I think 0.3 is a good value, too.

Hajduk: Sure, but for particles with $m$=1 g.
RESULTS OF RADAR OBSERVATIONS OF THE ORIONID AND ETA AQUARID METEOR SHOWERS CARRIED OUT IN BRATISLAVA (CZECHOSLOVAKIA) AND BUDRIO (ITALY) WITHIN THE IHW PROGRAM ARE COMPARED WITH THE SIMULTANEOUS DATA FROM ONDREJOV (CZECHOSLOVAKIA). THE ACTIVITY OF THESE SHOWERS IS STUDIED IN THE RELATION TO THE MOTION OF LARGE PARTICLES EJECTED FROM THE COMET. THE ACTIVITY WAS FOUND TO BE INDEPENDENT ON THE APPROACH OF THE PARENT COMET.

1. INTRODUCTORY NOTES

Two meteor showers, the Eta Aquarids in early May and the Orionids in late October, have a long-recognized association with comet Halley. Recent simultaneous observations of the showers in Czechoslovakia, USSR and Italy (Hajduk et al., 1984; Cevolani and Hajduk, 1984; Hajduková et al., 1986) revealed structural features not well explained by the previous toroidal model of the stream. McIntosh and Hajduk (1983) show that particles ejected from the comet will be dispersed over a segment of a shell which thickens to form a belt. The present orbit of the comet is not too far from the edge of the belt, whereas at the time of the showers the Earth passes through the belt closer to its mid-line; the Eta Aquarids passage is above the mid-line, and the Orionid passage below. This "shell model" is consistent with the small difference of the observed activity of both showers as well as with their almost identical width. Changes in nodes and periods give a good explanation of the filamentary structure of the stream.

A schematic representation of both observed meteor showers within the spread of the orbits is given in Fig. 1, with the full line belonging to the orbit of the comet. The points represent the past nodes of the comet orbit for each fifth of its returns back up to 1404 B.C. The zones of increased particle flux density are assumed to represent the belts corresponding to the individual libration cycles of the comet. The cross-section of the stream is shown in Fig. 2.

Fig. 1. A schematic representation of the shell of orbits of comet Halley from 1404 B.C. up to its present return. The points correspond to the nodes of each fifth return; at the longitudes of both meteor showers (Orionids and Eta Aquarids) the activity of the showers is sketched. (Symbols: q is the perihelion distance, Ω the longitude of the ascending node, γ the position of the vernal equinox, ω the argument of perihelion.)

2. OBSERVATIONS

The program of simultaneous observations of the Orionid meteor shower at Ondrejov Astronomical Observatory (50° N, 15° E) in Czechoslovakia and at the Budrio radar station (44° 35' N, 12° E) in Italy, were carried out in the second half of October, starting from 1978. For the overlapping periods of both series of data from 1981-86, the shower-to-sporadic background ratios R deduced from the range distribution are represented in Table 1. The range distribution of the recorded meteor echoes has been used to determine the shower radiant transit, and hence to discriminate the shower from sporadic meteors (Hajduk and Cevolani, 1981). In order to compare the data, the ratios R are normalized to the same mean value each year for both sets (Fig. 3). The discrepancies in the two trends especially in 1984 at Ls = 210 indicate possible contamination of the echo counts by the Epsilon Geminids, a minor shower whose meteors occur in larger distances of record at both stations. Differences in the observed echo rates enlarged. The range distribution method shows that maximum contributions of Epsilon Geminids were recorded on October 24 (Ls = 210.5) in 1984, but also on October 27 (Ls = 213.7) in 1983. A characteristic double peak in the 207-211 solar longitude interval is seen very often but it is completely absent in 1983 from both stations. This is rather unusual for Orionids and it can be explained only by a higher diffusion of particles in the central belt of the stream, probably caused by planetary perturbations.

Fig. 2. A suggested schematic view on the cross-section of comet's stream, consisting of about five belts of higher particle density (i is the orbital inclination, P⊙ the pole of the ecliptic, Perib the pole of the comet orbit, Ls the solar longitude).

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Fig. 3. The Orionid meteor shower activity in 1981-1986. The mean shower-to-sporadic ratios $R$ during the shower period. The data from 1986 are preliminary.
The activity, expressed in shower-to-sporadic background ratios of echoes along the solar longitude transit of the shower radiant, has been analysed during 2 hours around the time by the International Halley Watch (IHW) program hence moving in the vicinity of the comet itself. Several authors (Yeomans, 1977; Buhagiar, 1986) have suggested an increase of the meteor rates, as interval of October 16-29, 1985 and May 1-14, 1986.

In connection with the close approaches of the comet to the Earth’s orbit in October 1985 during the Orionid shower period (0.154 AU) and in May 1986 during the period of the Eta Aquarids (0.065 AU), some authors (Yeomans, 1977; Buhagiar, 1986) have suggested an increase of the meteor rates, as a consequence of a possible cloud of particles ejected from the comet in the previous returns and hence moving in the vicinity of the comet itself. This would require either the existence of a broad cloud of particles around the comet, or the validity of the toroidal model of the stream with an increasing density towards the present orbit of the comet. Neither of these models, however, seem to correspond to the recent observations of the comet Halley meteor showers.

Observations of the Orionid and Eta Aquarid meteor showers carried out simultaneously at Ondrejov (CSSR) and Budrio (Italy) have been extended in the 1985-86 years to cover the periods proposed by the International Halley Watch (IHWS) program (Babadzhanov et al., 1985). The total number of about 10000 radar meteor echo, recorded in the interval of October 16-29, 1985 and May 1-14, 1986, during 2 hours around the time of the median transit of the shower radiant, has been analysed. The activity, expressed in shower-to-sporadic background ratios of echoes along the solar longitude has been analysed.

### Table 1. Shower-to-sporadic ratios R of radar meteor echo rates (R(B)Budrio data, R(0)Ondrejov data), deduced by the method described in Hajduk and Cevolani (1981).

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Fig. 4. The activity variation (in shower-to-sporadic background ratios) of meteor echoes during the shower period (in solar longitudes, Ls) from simultaneous observations, Δ min denotes the position of the minimum distance between the orbit of the comet and Earth.

3. Observations in 1985-86 at the approaches of the comet

In connection with the close approaches of the comet to the Earth’s orbit in October 1985 during the Orionid shower period (0.154 AU) and in May 1986 during the period of the Eta Aquarids (0.065 AU), some authors (Yeomans, 1977; Buhagiar, 1986) have suggested an increase of the meteor rates, as a consequence of a possible cloud of particles ejected from the comet in the previous returns and hence moving in the vicinity of the comet itself. This would require either the existence of a broad cloud of particles around the comet, or the validity of the toroidal model of the stream with an increasing density towards the present orbit of the comet. Neither of these models, however, seem to correspond to the recent observations of the comet Halley meteor showers.

Observations of the Orionid and Eta Aquarid meteor showers carried out simultaneously at Ondrejov (CSSR) and Budrio (Italy) have been extended in the 1985-86 years to cover the periods proposed by the International Halley Watch (IHWS) program (Babadjavan et al., 1985). The total number of about 10000 radar meteor echoes, recorded in the interval of October 16-29, 1985 and May 1-14, 1986, during 2 hours around the time of the median transit of the shower radiant, has been analysed. The activity, expressed in shower-to-sporadic background ratios of echoes along the solar longitude, has been analysed.

Fig. 5. Mean meteor echo hourly rates for the central part of showers (heavy lines) and peak rates (light lines) for all echoes N_{all} (upper part) and for long duration echoes N_{ls} (lower part).

Ls, is shown in Fig. 3 (Orionids 1985) and in Fig. 4 (Eta Aquarids 1986). The level of activity for both showers is lower than the mean values in other years and the activity variations are typical.
Although no fixed positions of the activity maxima in both showers have been detected in reported results of simultaneous observations, the present results show clearly that, at least for the particle masses $m > 10^{-5}$ kg, the particle space density in the distances between 0.065 and 0.124 AU from the comet orbits (i.e. in the minimum distances between the orbits of the comet and the position of the Earth in the period of the Eta Aquarid and Orionid showers respectively), was not increased as a consequence of the approach of the parent comet. Fig. 5 shows that the mean activity of the central parts of the showers, between $44 < L < 48$ and $306 < L < 310$, as well as the peak values from the whole shower period as observed at Ondrejov in different years, are considerably lower in the years 1985 and 1986 than in the previous years and, over a longer time scale, lower than the average values (Fig. 5, upper part). Wood (1985) confirms the moderate activity of Eta Aquarids 1985 return and Milutchenko (1987) the low activity of the central part of Orionids in 1985. The trend appears somewhat different in the range of large particles with durations $t > 1$ sec. (Fig. 5, lower part). The observed decrease in the rate of long-duration echoes $N_{LS}(t > 1$ sec) is smaller for the Orionids 1985 and Eta Aquarids 1986 in comparison with the decrease in the rate of all echoes $N_{LL}$. The proportion of long-duration was therefore larger than in the last years. Hence the recent decrease of the meteoroid flux is caused mostly by the absence of small particles.

REFERENCES


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Pre-ablation heating was extensively studied since the beginning of the physical studies of meteor events. Pioneering works were published by one of the most famous scientists who began to develop the theory of the heating, by Levin (1956). Other contribution was made by Cepiecha and Padevč (1961) and by others, recently by Kruchinenko (1986). From the mathematical point of view, the problem consists in the solution of the heat transfer equation subjected to the appropriate initial and boundary conditions. In general, the solution is not easy to obtain if realistic situation is to be described. Therefore, some authors have simplified the problem by assuming the meteor body can be approximated by infinitely long cylinder. Then the solution could be found in the relatively simple analytical form. But this assumption seems to be highly unrealistic. Therefore, the theories dealing with, say, realistic shape of meteoroids should be preferred.

All analytical solutions were obtained under the assumption that the body is not subjected to any deceleration during its flight. This can be true for sufficiently large bodies. But in case of small bodies, they can significantly decelerate and, moreover, thermal radiation from their surfaces can dominate the effect of thermal conduction into the centre, which highly complicates the whole situation. Then, the theoretical beginning heights of meteors can be in doubt. Micrometeorites can not even constitute the visible trajectory. Also the frequently used assumption of the exponential atmospheric profile can substantially change the conclusions obtained. The portion of flight in the pre-ablation heating conditions is undoubtedly the largest one from all of them. Therefore, the knowledge of precise atm. profile is of great importance. Also possible rotation of the heated body was not considered so far. All these mentioned problems are worth solving to ensure further development of meteor physics. As for me I believe that this is possible using the modern computing technique available at present. The theory of meteoroids heating depends on such physical parameters as thermal conductivity of the material, its capacity and bulk density. These parameters can be, on the other hand estimated to some extent by the knowledge of the thermalization curve. The great part of this curve comprises the temperature region giving the radiation inside the infrared range. Therefore, the infrared observations made either on the ground (if possible at all) or aboard the Earth orbiting satellites can significantly contribute to our understanding of the whole pre-ablation process. Maybe they can most simply be accomplished as a by product of the remote sensing of the Earth surface.

After reaching sufficiently high temperature, the meteoroid can start to ablate, which itself makes it possible, the meteor to be directly observable either by optical or radar methods. Let us mention first the general features or problems. The motion of each meteoroid during its flight in the atmosphere is governed mainly by the drag force, the slowest of them can significantly be subjected also to the Earth's gravitation force. Let us neglect this force in our further considerations. Then the drag equation takes the form

\[ \dot{m} = \frac{\mu m}{\rho v^2}, \]

(e.g., Bronshten - 1981). As already stated, sufficiently high temperature leads to the evaporation of the meteoroid's material from its surface. This process is believed to be governed by the evaporation equation

\[ \dot{m} = -\frac{1}{S} \rho v \dot{\lambda} v^2, \]

(Bronshten, 1981). The quantities entering those two equations have the following meaning:

- \( m \) - is the instantaneous meteoroid mass,
- \( v \) - its velocity at the same time instant,
- \( S \) - effective cross-sectional area of the body,
- \( \rho \) - the air density at the point at which the meteoroid velocity equals to \( v \),
- \( \dot{\lambda} \) - the drag coefficient,
- \( Q \) - the heat of ablation of the meteoroid material,
- \( \lambda \) - the heat transfer coefficient.

As is well known, these two equations possess the first integral of the form (e.g., Bronshten - 1981):

\[ m m_0 \exp \left[ \frac{(v - v_\infty)}{v_\infty} \right], \]

where \( m_0 \) and \( v_\infty \) are the pre-atmospheric values of the corresponding quantities and \( \sigma = \lambda (Q) \) is the ablation parameter. It is necessary to stress that the integration was performed under
the assumption of $a$ being constant. The integration

$$\int (1 - \frac{v}{v_\infty}) - \int (1 - \frac{\sqrt{v}}{6}) = \frac{2K \exp (\sqrt{\frac{v}{v_\infty}})}{\int \frac{m_\infty \cos I}{b \sin \gamma R}}$$

where $\int (1)$ is the exponential integral, $b$ stands for the air density gradient, $I_0$ is the zenith distance of the meteor radiant and $K$ is the shape-density coefficient. By the year 1983, these relations served as a basis for the comparison of theory with observations. They give the dependence of $v$ and $m$ on the measurable height (through $I_0$) or time. But $v$ as well as $m$ are not directly observable quantities. $v$ must be obtained by numerical derivative of measurable height passed by meteoroid in its flight. Because it is known from numerical mathematics that numerical derivative could be highly unprecise depending on the quality of input data, it is clear that conclusions based on them can be scarce. It was believed that the integrations presented so far are all which can be done in solving the basic equations. But surprisingly, Pecina and Ceplecha (1983) have proved the existence of the third integral giving the dependence of distance $l$ along the trajectory on the velocity $v$. So they obtained the complete integral of basic equations of motion and evaporation $l = l(t)$ in the parametrical form, the instantaneous velocity $v$ being the main connecting parameter. It is necessary to remind that $l$ is a directly observable quantity in photographic observations. The problem with which it can be determined is only several tens of meters depending on equipments used. Using the new integrals the authors have arrived at the conclusion that it is necessary to use the instantaneous atmosphere for bright meteors (i.e. for fireballs) (e.g. in the interpolation table form). Other conclusion lies in the finding that using the exponential atmosphere one can lead to errors in prediction of $v_m$, which can then be far outside the three standard deviation box and, therefore, can significantly influence the prediction of the heliocentric orbit of meteoroid under consideration. The second integral must then be replaced by

$$\int (1) - \int (1 - \frac{\sqrt{v}}{6}) = \frac{2K \exp (\sqrt{\frac{v}{v_\infty}})}{\int \frac{m_\infty \cos I}{b \sin \gamma R}}$$

for details see Pecina and Ceplecha (1984). The function $f_{\infty}^{\sin \gamma \theta_d\phi}$ can be easily tabulated. The general statement can be established: the new form of the second integral must be used in each case in which the integration is made from some point of the light (or ionization) curve to infinity! Other investigation made by Ceplecha (1983) has revealed the fact that even one atmosphere used for all fireballs in the whole year can significantly change the results on $v_\infty$ and $a$. He concluded that the instantaneous (i.e. for example for every month different atmosphere) must be used in order to obtain reliable results on $v_\infty$ and $a$. Computations and their comparison with observations lead to the conclusion, that the assumption of constant $a$ and $K$ is mostly quite acceptable. The theoretical trajectory fitted the observed very well and errors of 1 following from the new method are well comparable with those from the geometry of problem. Another very significant conclusion is valid with respect to the determination of ablation parameter $a$. The new method can get it with the accuracy never previously reached (several percent for good observations). Statistics of ablation coefficients determined from this method is significantly better and enables better classification of meteoroids.

The results and conclusions discussed so far are not dependent on the light curve itself. If we want to determine other parameters of meteoroids we must add to the basic set of equations, in optical case, the luminous equation

$$l = \frac{\tau}{\cos \gamma} \frac{m_\infty}{v_\infty}$$

where $\tau$ is called luminous efficiency. As shown by Pecina and Ceplecha (1983) the present expression for $l$ can be considered the most general possible with $\tau$ depending on velocity $v$. Interesting effect arises when integrating the drag equation and determining the meteoroid mass $m_\infty$ (dynamical) and integrating the luminous eq. for obtaining the other mass $m_\infty$ (photometrical). In most cases they differ and usually $m_\infty < m_\infty$. If requiring $m_\infty = m_\infty$ we obtain bulk densities of meteoroids lower than the corresponding density of water. But this contradicts the fact, that many meteorites deposited in various museums have bulk densities well comparable with Earth's materials. Podvět (1977) made an attempt of avoiding the problem of low densities by introducing the notion of dynamically significant coma which led him to the conclusion that $S$ in the drag equation cannot coincide with the same quantity in the evaporation equation. The criticism of Bronštěn and Stanjukovich (see Bronštěn's book - 1981) meant that this idea had to be abandoned. The principal equations of meteor physics were also modified for faint meteors to explain their shorter light and ionization curves (in comparison with those following from the single-body theory). The interested reader can see Kashcheev et al.,(1967) work or Bronštěn book. Recently, when dealing with deceleration and bulk densities of faint photographic meteors, Lebedinets (1977) (together with Nisov et al. (1984 a,b)) have developed a theory of quasi-continuous fragmentation of meteor bodies. Lebedinets conclusion can be summarized by the statement that only $3$ meteorites from $32$ sporadics were produced by low density (fluffy) particles. The author of present work is convinced that the same fact could be revealed by the classical single-body theory. The measure for the ablation type is the ablation parameter $a$. Higher values of this parameter can lead to the conclusion, that the fragmentation where the fragments are negligible in comparison with the parent body. If the parent body would disintegrate into a few comparable debris, the single-body theory must surely fail.
The other problem consists in the fact that for application of new equations to observed meteors, the number of measured distances along the trajectory should be sufficiently high for getting reliable results. But this is not the case for faint meteors. On the other hand, long and bright fireballs offer when using this method, the possibility of studying, for example, the variability of $\sigma$. If the values were known from other investigation, we could ascribe the observed differences between observed and theoretical distances to the effect of the atmosphere in comparison with the used one. Thus, some meteors can serve as natural and not expensive indicators of the instantaneous state of the middle atmosphere. As for the bulk densities of meteoroids, the work of Pecina and Ceplecha (1984) leads to another conclusion: use of the exponential profile of the atmosphere can cause considerable decrease of the bulk densities (in the cases presented 43% and 92%). From this fact the importance of the knowledge and, namely, the usage here of the atmospheric model is again clearly visible. Another improvement of the observational possibility is represented by the new television technique which is capable of registering the meteors down to 9th magnitude. As TV observations will develop, the new theory of meteors becomes more and more than micrometeors should probably be improved. As shown by Millman and Clifton (1979), this technique is capable of providing us also with high quality spectral information. Unfortunately, Millman's pioneering work was not followed by anybody. Spectral data can get information on the conditions in meteoric plasma and the chemical composition as documented by Ceplecha (1973). His work was done under the assumption of local thermodynamic equilibrium which is probably not true. But since that time the knowledge of spectral line formation has further developed and, therefore, it is worth trying to apply these new ideas to the physics of meteor spectra. It is believed that the end height theory can provide us with other information on meteoroids. Particularly, this theory was used here for the attempt at solving this theory to solve the problem of the origin of meteoroids. His theory seems to be still at start because of some semi-empirical criteria which, I think, should result from the theory itself. Yet, Millman (1973) have also reported some documented falls of meteorites and established some conditions on end heights which would ensure that meteoroid can be expected to get meteorite fall. The cause of fragmentation observed seems not to be well understood. McCrosky and Ceplecha (1970) have considered the disruption due to thermal stresses. Padevèt (1979) and others (see Bronshint's book - 1981) have assumed that the fragmentation was due to loading pressure of the atmospheric drag. In Bronshint's book the possibility of emitting electrons from surfaces of solid bodies is mentioned. If the outflow of electrons from body prevails over the influx, the body will get the positive charge which would contribute to its easier disintegration. The best observational evidence of meteoroid fragmentation was obtained by Babadzhanyan and Getman (1980) and Babadzhanyan (1983) by method of very short (instantaneous) exposure. To terminate the section on light effects we will mention trains left by meteors which persist up to several dozens of minutes. Their nature seems to be unclear at present. The other set of effects connected with meteors is the consequence of the fact that meteoroids flying through the atmosphere can leave behind themselves trails consisting of weakly ionized plasma. In order to construct the theory of these events we must add ionization equation

$$\varphi V = - \beta m$$

as the electron line density in the train, $V$ is the mass of the atoms ablated from the surface of the meteoroid and $\beta$ is the ionization probability which is considered a function of $V$. Because $\beta$ plays the same role as $\gamma$ in the luminous equation it is clear that its knowledge is of great importance. It seems that the most used form is $\beta = \beta_0(\gamma - 8.8)$ with the same $\gamma$. He believed his probability better coincides with the reality. But there are also scientists saying we don't have the satisfactory formula for $\beta$ (e.g., Jones, 1984). It seems, therefore, that the improvement of our understanding of $\beta$ is necessary. The theory of scattering of radio-emitted radio waves from meteor ionization has a principal significance for meteor radar physics. The first extensive work was published by Millman and Clifton (1952) and followed then by Lebedinets and Sosnova (1968a,b) and (1969), Jones and Collins (1974), Poulter and Baggaley (1977), Chumak and Mojsja (1977), Solyank and Tkachuk (1983) and many others. It seems from the study of these papers that the theory still remains somewhat insufficient. For example, the resonance of polarization ratio $g_{1}/g_{2}$ (g being scattering coefficient) of the order of 100 found by Lebedinets and Sosnova as well as by Jones and Collins was according to Chumak and Mojsja (1977) never observed. Moreover, in the discussion in literature it was stated, that the inconsistency of theory with observations can be due to wrong sign of imaginary unit used in computations. I am convinced this cannot be true in the physical reality. I think it is connected with the approach to the problem itself. Any way, common conclusion can be drawn. The echoes from meteor ionization can be divided into two main categories. The first one is usually designated as underdense and the second one as overdense. Two main types of echoes are completed by transient and loss. A much better understood type of reflection is the underdense than the overdense one. The underdense scattering from forming trail enables the meteor velocities and ambipolar diffusion coefficient to be determined. When Fresnel characteristics are employed the shape of amplitudes and their decay can largely be influenced by delonization processes causing faster decrease of electron volume density $n_e$ inside the trail. The main factor affecting the duration of echoes is believed to be the ambipolar diffusion. The other possible processes such as recombination, attachment and others were reduced to the attachment itself. The extensive studies of these processes were published by Baggaley (e.g. 1972, 1978) and (1980). Present concept prefers the view that electrons do attach to atoms ablated from the meteoroids (Bibarsov, 1972). The behaviour of $n_{e}$ under this process is described by Bibarsov et al. (1980). A minor objection can be raised against the value of their attachment coefficient, which was determined from photographic observations of only three meteors with large scatter of resulting values. It is also possible that the attachment coefficient depends on the chemical composition of the meteoroid. As shown by Novikov et al. (1979), the formation of negative ions and their presence inside the trail can significantly change the shape of echo amplitude. It is possible to obtain an underdense echo followed after a short time.
that meteor trains are sources of their own first one is connected with the possibility of unresolved problems of meteor physics. At the end of this part I would like to point out a unclear (see, e.g. Bronshen - 1981). At the named head echoes: only limited information has been published by Boykov (1986). is known about them and their nature is still studied. Theoretical background of the underdense. Therefore, its other development is extremely needed. By analogy with optical spectral research, there is the possibility to learn more of the conditions governing the evolution of ionized meteor trails from the study of the profiles of observed radar pulses (analogy to the study of the profiles of spectral lines in optical branch). Theoretical background has been published by Boykov (1986).

A small portion of echoes was observed, named head echoes. Only limited information is known about them and their nature is still unclear (see, e.g. Bronshen - 1981). At the end of this part I would like to point out a few unresolved problems of meteor physics. The first one is connected with the possibility that some meteor trains are a dying of develop it further. Hawkes and Jones (1978) have pointed out the possible connection of the rotation of the meteoroid body with the initial radius. All I said so far could be connected mainly with underdense echoes. The theory of overdense echoes seems to be worse than the theory of the underdense. Therefore, its other development is extremely needed. By analogy with optical spectral research, there is the possibility to learn more of the conditions governing the evolution of ionized meteor trails from the study of the profiles of observed radar pulses (analogy to the study of the profiles of spectral lines in optical branch). Theoretical background has been published by Boykov (1986).

...
DISCUSSION

Babadzhanyan: Photographic observations of meteors by the method of instantaneous exposure and theoretical investigations are indicative of quasi-continuous fragmentation of meteoroids. This phenomenon strongly affects the observed light-curves of meteors. But in your presentation you did not mention this.

Pecina: The limited time span prevented us from doing so, but it is mentioned in the paper.

Padevet: The single body theory of meteors described by dr. Pecina does not contain the theory of end heights of meteors; therefore, the end heights of fireballs cannot be determined from this theory without empirically fixed end invariants. We have to construct a more general physical theory of meteors for this purpose.
The photometric light curves of bright Geminids are investigated. The analysis of the light curves reveals a peculiar nature of meteor luminosity with rapid flickering and small brightness fluctuations. This peculiarity of the luminosity of the bright Geminids points to a certain ablation process of these meteoroids in the Earth's atmosphere. According to estimates of the energy of ablation a conclusion was made that the investigated Geminid meteoroids were disrupted in the atmosphere by the melting and cyclic ablation of the surface-layer of meteoric matter.

The photometric data of bright Geminids allowed to reveal a peculiar nature of the meteor luminosity with rapid flickering and small brightness fluctuations. A period of the flickering of the Geminids is nearly an order less than that of early known flickering meteors (Kramer, 1966).

Beginning from the middle of the trajectory the flickerings become stable with small brightness fluctuations.

In the papers on the meteor flickering phenomenon (Kramer, 1966) it has been established that light pulsations are expected to occur only with the meteors produced by massive meteoroids deeply penetrating into the atmosphere; and the amplitude and the period of brightness fluctuations vary with a meteoroid penetrating deeper and deeper into the atmosphere.

It should be noted, however, that regular flickering is observed not for all meteors produced by large meteoroids and deeply penetrating into the atmosphere.

The present paper investigates the mechanism of desintegration of the Geminid meteoroids in the atmosphere. We have studied the light curves of the three flickering Geminids No 643881, No 761683 and No 821691 photographed in Dushanbe. For these Geminids the stable regime of rapid flickering of small amplitude (~0.5) is set up from the middle of meteor trajectory approximately at the height of 75 km and lasts till the end of the flight.

Calculated data for these meteors are given in Table 1 in which the data on the flickering meteor No 60c studied by Halliday (1963) are shown for comparison as well. Fig. 1 presents the light curves of Geminids.

**Table I**

<table>
<thead>
<tr>
<th>No</th>
<th>643881</th>
<th>761683</th>
<th>821691</th>
<th>60c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year, month</td>
<td>64.XII</td>
<td>76.XII</td>
<td>82.XII</td>
<td>60.XII</td>
</tr>
<tr>
<td>V (km/s)</td>
<td>4.7</td>
<td>3.4</td>
<td>36.4</td>
<td>26.1</td>
</tr>
<tr>
<td>H (km)</td>
<td>95.7</td>
<td>87.2</td>
<td>92.7</td>
<td>72.7</td>
</tr>
<tr>
<td>H^2 (km)</td>
<td>60.8</td>
<td>61.4</td>
<td>64.8</td>
<td>61.4</td>
</tr>
<tr>
<td>H^2 / H (km)</td>
<td>53.0</td>
<td>&lt;61</td>
<td>51.8</td>
<td>46.6</td>
</tr>
<tr>
<td>n (s^2)</td>
<td>3682</td>
<td>5499</td>
<td>2186</td>
<td>-</td>
</tr>
<tr>
<td>n^2 (s)</td>
<td>1.35</td>
<td>1.33</td>
<td>1.19</td>
<td>0.84</td>
</tr>
<tr>
<td>η (s)</td>
<td>-72</td>
<td>-57</td>
<td>-48</td>
<td>-40</td>
</tr>
<tr>
<td>η (s^2)</td>
<td>11.62</td>
<td>&gt;19</td>
<td>10.04</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 1. The light curves for the Geminids. Shutter breaks enable to measure with high accuracy the time intervals between the two subsequent flickerings. The variation of the frequency of flickerings N versus the height H is plotted in Fig. 2. It is seen from Fig. 2 that the frequency of flickerings increases continuously with an accompanying decrease of the height from 111 s^-1 to 490 s^-1 for the meteor No 643881, from 35 s^-1 to 350 s^-1 for the meteor No 761683 and from 83 s^-1 to 625 s^-1 for the meteor No 821691.

It is interesting that our estimates of periods of the Geminid flickerings, decrease in the periods of these flickerings versus time and the height range where pulsations occur coincide completely with Hallidays photographic data of the Geminid No 60c observed in Canada (Halliday, 1963). This points to the fact that rapid flickering for the meteors of such type is distinctive feature of the luminosity of the bright Geminids in the atmosphere.

The autowarly nature of evaporation has been supposed to explain the observed flickering phenomenon. A fluctuation may be set up when the pressure of saturated vapors and the outer pressure regular each other automatically (Oleak, 1964; Kramer, 1966).

The calculation of the heat-conductivity equation:

\[ \frac{\partial \delta}{\partial t} = \frac{\partial}{\partial x} \left( \frac{K}{\rho c} \frac{\partial \delta}{\partial x} \right) + \frac{1}{c_0} \left( \frac{\partial \delta}{\partial t} \right)^3 \]

at boundary conditions

\[ T (x = 0, t = 0) = T_m \]

has the form:

\[ T_v = \frac{\Delta \rho y^3}{4 \delta c} \frac{\delta_0}{\Phi (\delta_0)} + T_m \]
where \( g = \lambda / \sigma c \) and \( \lambda, \delta, c \) are the heat-conductivity, the specific heat and the density of a meteoroid respectively; \( \lambda, \sigma, c \) and \( V, \rho, H \) are the velocity, zenith distance and the atmospheric density for a given height (CIRA, 1972); \( R \) is the scale height; \( \dot{\gamma} \) is the period of flickering; \( T_m \) and \( T_v \) are the melting and boiling temperature; \( \Phi(y) \) is the integral of the probability; \( \delta(x) \) is the Dirac delta-function.

As \( k \) is sufficiently small (0.006 < \( k < 0.01 \)) we may assume \( e^{k \gamma t} \approx 0 \) and \( \Phi(k \gamma t) \approx 2 \sqrt{k \gamma t} \). Then using the equation (3) we obtain the expression for the heat-transfer coefficient:

\[
\Lambda = \frac{4 \sqrt{\lambda \sigma c}}{\sqrt{\dot{\gamma}}} \left( \frac{A}{B - 12 \rho t^3} - T_m \right),
\]

where \( A \) and \( B \) are constants characterizing the chemical composition of meteoric matter (Allen, 1973).

Using the equation (4) and the obtained values of the period of the flickering \( \dot{\gamma} \) for several points of meteor trajectory there were three types of meteoroids, namely for crumbly stone, stone and iron meteoroids. For the case of crumbly stone meteoroids there were no accuracy between the calculated and observed values of the period of flickering at any values of the heat-transfer coefficient \( \Lambda \). This fact allowed to exclude the crumbly stone composition for the Geminids.

The values of \( \Lambda \) were obtained for the stone and iron meteoroids and it turned out that they vary along the meteor trajectory. The variation of \( \Lambda \) versus height is shown in Fig. 3. As is seen the heat-transfer coefficient decreases continuously when a meteoroid penetrates into the depths of the atmosphere.

<table>
<thead>
<tr>
<th>No</th>
<th>( \dot{\gamma} )</th>
<th>( \Lambda )</th>
<th>( Q ) erg/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>643881</td>
<td>I</td>
<td>0.00940.002</td>
<td>0.0840.022</td>
</tr>
<tr>
<td>76163</td>
<td>II</td>
<td>0.02540.003</td>
<td>0.0420.026</td>
</tr>
<tr>
<td>621691</td>
<td>II</td>
<td>0.0120.0016</td>
<td>0.0460.027</td>
</tr>
</tbody>
</table>

Using the luminosity equation:

\[
I = \frac{1}{2} \hat{I} (\frac{d \rho}{dt})^3
\]

and the equation of mass loss:

\[
\hat{m} = \frac{\Lambda \delta \rho^3}{dt} \frac{I}{2Q}
\]

we can obtain the following expression to calculate the parameter \( \Lambda/Q \):

\[
\frac{\Lambda}{Q} = \frac{2^{1/3}}{\delta \rho^3} \frac{I}{\alpha \rho^3 (I/t^3)^{1/3}}
\]

The parameter \( \Lambda/Q \) was calculated for the several points of meteor trajectory. Here \( \alpha, \gamma, \rho \) are the middle, the form and the luminosity factor respectively. According to the obtained from (4) values of \( \Lambda \) and from (5) values of \( \Lambda/Q \) we have found the energy of ablation \( Q \) which also vary with height. The increase of \( Q \) appears to occur at these segments of the meteor trajectory where the decrease of the luminosity is observed. The value of \( Q \) decreases at the increase in the luminosity and reaches its minimum at the maximum meteor brightness.

Analysis of instantaneous images the bright Geminid No 821691 indicate that this meteor have wakes. As was shown by McCrosky (1958), Babadzhyan and Konovalova (1963) the formation of meteor wakes is connected with the separation of meteoroid matter from the parent body. Meteor wakes available for the Geminids as well as the obtained values of \( \Lambda/Q \) we have found the energy of ablation \( Q \) which also vary with height. The increase of \( Q \) appears to occur at these segments of the meteor trajectory where the decrease of the luminosity is observed. The value of \( Q \) decreases at the increase in the luminosity and reaches its minimum at the maximum meteor brightness.

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References
Kramer, B.N.; 1966, Problems cosmich. fiziki. 1, Meteoroy, p. 75.
Grün: You suggested that flickering may also be caused by spin (rotation) of the particle. If this thesis can be proved, then one has finally a method to determine the spin of meteoroids, the knowledge of which has great implications in the dynamics of meteoroids (Yarkovsky–Radzievskij effect).

Babadzhanov: Until now, we did not consider the influence of meteoroid rotation on flickering of Geminid meteors. But this we could do in a close future.
THE TRUE HEIGHT DISTRIBUTION AND FLUX OF RADAR METEORS

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When compared to satellite detector measurements of dust particles of mass \(< 10^7 \text{g}\) and optical meteor observations for mass \(> 10^9 \text{g}\), the flux of the interstellar radar meteors is discrepant: the radars record fluxes which seem too small by a factor of about 20-30. This has usually been explained as being due to the majority of the flux being held in low-velocity meteors which produce little ionization and hence have limited radar detectabilities.

We propose an alternative hypothesis: that the discrepancy is due to wavelength-dependent effects, implying that conventional meteor radars (\(f > 20 \text{ MHz}\)) only detect the lower-altitude underdense meteors. To test this we have determined the height distribution of radar meteors at 2 and 6 MHz, at which frequencies the echo ceilings are much higher than the 100-105 km limits of VHF radars. We find that the distributions peak at 105 km, fully 10 km above the peaks of VHF radars, with many meteors occurring to at least 140 km altitude. Additional observations using the powerful Jindalee radar in central Australia confirm these results, and show that the cumulative flux of particles of mass \(> 10^7 \text{g}\) is about \(9 \times 10^8 \text{m}^{-2} \text{sec}^{-1}\); this is consistent with satellite data and is over an order of magnitude larger than derived in previous radar meteor experiments.

1. Introduction

The fact that VHF meteor radars are unable to detect many meteors at height above 100-105 km, the so-called 'underdense echo ceiling', is well-known (McKinley, 1961). In an important paper by Ekvall (1963) studied the implications of the echo ceiling and showed that the true height distribution, and hence true flux, could only be determined by using a radar of much lower frequency than usually utilized: meteor radars have most often operated at around 20-60 MHz, and Greenhow pointed out that a radar at a frequency of just a few MHz was necessary in order to detect the high-altitude underdense meteors. One of us (Elford, 1980) has previously presented some results gained at 2 MHz, and suggested that the majority of the flux small meteors has remained undetected since it ablates above the echo ceiling of VHF radars. This fits well with the known discrepancy in the radar meteor flux when compared to the flux of dust particles measured by satellite instruments and the flux of larger, optical, meteors (Hughes, 1978).

This leads us to the hypothesis that rather than the low ionization-efficiency of slow meteors (e.g. Cook et al., 1972), in fact it is the wavelength-dependent selection effects (described in section 2) that are the origin of the discrepancy.

In order to test our hypothesis we have determined the height distributions of underdense meteors using radars of frequency 2 and 6 MHz (i.e. HF radars); for comparison purposes the height distribution from a VHF radar (\(f = 54 \text{ MHz}\)) is also given. The HF distribution indicates that the bulk of meteors actually occur at too high an altitude to be detected by VHF radars. Although these HF height distributions are remarkably different from those gained at VHF, in fact they are as expected from single modelling based upon standard echo attenuation factors, and are also in agreement with other forms of observation not limited by echo ceiling effects (e.g. Evans, 1966; Hawkes and Jones, 1980; Cook et al., 1980).

Additional observations have been made at a variety of HF frequencies using the Jindalee over-the-horizon radar in central Australia. This radar is, we believe, the most powerful ever used for meteor detection, having a limiting magnitude of between +16 and +17. The results back-up our hypothesis and lead to a value for the total influx in the mass range \(10^{-6} \text{m} < m < 10^{-2} \text{g}\) which is about 30 times the previous estimates; the total mass influx \((10^{-7} \text{c} < m < 10^{-2} \text{g})\) as a result is about four times the previous estimate, and is of the order of 15,000 tonnes per year (Thomas et al., 1986).

2. Factors affecting the radar meteor height distributions

The data presented in this paper were largely gained at much lower frequencies than most meteor researchers will be familiar with, and therefore as a starting point we will describe the factors affecting underdense radar meteor height distributions using as an example the distribution as observed at 54 MHz; this frequency is much nearer to those utilized in the vast majority of meteor radars.

In Figure 1 we show the height distribution of 2302 sporadic radar meteors determined using our 54.1 MHz radar at Buckland Park (40 km north of Adelaide; latitude 35°S). The transmitter power is quite low (a few kWatts) but the same high-gain antenna array (a filled square 80 x 80 m) is used for both transmission and reception, and in addition a microprocessor system is used to accomplish coherent signal acquisition and averaging: the limiting meteor line density corresponds to a magnitude \(M_\theta = -9\). The beam zenith angle \((z)\) is steerable along a line running approximately East-West, and in the present instance was set at \(z = 34^\circ\). Since the beam width (half-power, half-width) is only \(\pm 15^\circ\), the heights \((h)\) of individual meteors can be found directly from the \(h = R \cos z\), where \(R\) is the range. Instrumental limitations upon \(R\) lead to the cut-offs at \(h = 72\) and 106 km in Fig. 1. The data have been plotted as weighted number of meteors: that is, the effect of the increasing range and the changing atmospheric collecting area have been allowed for, and then the points were normalized to the peak at \(h = 92-93\) km. This height distribution is typical for VHF radars: a radar at \(f = 30 \text{ MHz}\) might show a slightly higher peak (at \(95 - 98\) km), but there is always a rapid fall-off above this, with few meteors above 105 km and almost none at \(h > 110\) km.

We have given elsewhere a modern review and discussion of the factors affecting the amplitude of a radar echo from an underdense meteor train during its formation and initial evolution (Olsson-Steel and Elford, 1986; 1987a,b; Elford and Olsson-Steel, 1987; Thomas et al., 1986, 1987), and these factors are only briefly mentioned below. Other recent work on this problem includes that of Poulter and Baggaley (1978) and Novikov et al. (1986). All attenuation factors \((g)\) given here are for attenuation of the returned amplitude rather than the power.

The initial radius \(r_0\) causes attenuation:

\[ a_r = \exp(-4 \pi \rho r_0^2 / l^2) \]

(1)
where $\lambda$ is the wavelength; $r_0$ (in metres) is given by:

$$
\log_{10} r_0 = 0.019 h - 1.92 + \log_{10} \left( \frac{V}{40} \right) \quad (2)
$$

(Baggaley, 1980a, 1981) where the height ($h$) is in km and the meteor velocity ($V$) in km/sec.

The finite-velocity effect is described by:

$$
a_v = (1 - \exp (-\delta)) / \delta \quad (3)
$$

where

$$
\delta = \left( 8 \pi^2 D / \lambda V \right) \left( \frac{2 R}{\lambda^2} \right)^{3/2} \quad (4)
$$

and the ambipolar diffusion coefficient $D$ is found from:

$$
D = 290 T^2 / p \quad (5)
$$

where the temperature ($T$) and the pressure ($p$) have values taken from the U.S.Standard Atmosphere (1976).

Radial diffusion of the train, usually recognized as causing decay-Type echoes, also cause attenuation since the first radar pulse to meet the train may do so some time after its formation: this would be an acute effect for low-prf radars, and some earlier work (Elford and Lindblad, 1978) was carried out with the Onsala meteor radar (prf = 50 Hz) especially in mind. If it is assumed that the train is formed just after the passage of a transmitted pulse through that volume of space then the attenuation factor is:

$$
a_d = \exp \left( -16 \pi^2 D / \lambda^2 \right) \left( \text{prf} \right) \quad (6)
$$

and this expression is used throughout the present paper. However, in reality the train may be formed at any time between pulses, and since the formation takes a finite amount of time one cannot assume that on average the train forms midway between pulses; the exact expression applicable will depend upon the criteria applied for the recognition of meteors (Elford and Lindblad, 1978). Later work will encompass a more rigorous expression for $a_d$ (Olsson-Steel and Elford, 1987b).

The total attenuation will be:

$$
a = a_r a_v a_d \quad (7)
$$

and for particular values of $\lambda$, $V$, $h$ and the prf the three attenuation factors make different contributions to $a$. It turns out that for the Buckland Park 54 MHz radar the $a_r$ term dominates except for low-velocity ($V < 25$ km/sec) meteors in which case $a_v$ is the most important; here we use in our model $V = 35$ km/sec (since the meteors are sporadics), and the prf = 1024 Hz. As a source function for our model we use, as justified later, a "true" number of meteors at height $h$ of:

$$
N_T (72 < h < 105 \text{ km}) = \left( \frac{h - 72}{33} \right)^2 \quad (8)
$$

and the number we expect to detect at any height is:

$$
N_E (h) = \alpha N_T (h) \quad (9)
$$

Meteors are only observed at one particular height using our equipments: we interpret this height as most probably being the height of maximum ionization.

In Fig. 1 the results of our calculation of $N_E (h)$ is shown as a solid curve. Clearly there is an excellent fit, giving us faith in this simple model, except possibly at $h > 100$ km where there are only about half as many meteors as the model predicts: we believe that this is an artifact of the data analysis (real-time minicomputer processing of signals output by the microprocessor) and the problem will be rectified in future experiments.

3. Height distribution at 2 MHz

At Buckland Park we have another radar which can be operated at either 2 or 6 MHz. The receiving array consists of a filled circle of dipoles, 1 km in diameter. By transmitting a wide beam, using a smaller array, and making phase comparisons between rows of antennas of known separation amongst the receiving array, the heights of radar meteors can be determined from the range and zenith angle determinations. Some earlier results were reported by Elford (1980), and the present experiment (which benefits from improved transmitter power, and real-time analysis of echoes using a minicomputer) has been described in detail by Olsson-Steel and Elford (1987a). The effective limiting magnitude is $M_V = +7$.

In Figure 2 we show the 2 MHz height distribution of 1461 meteors observed in 1985. Some of these meteors are Eta Aquarids, but predominantly they are from the various showers of July/August, and in particular the Delta Aquarids: for details see Olsson-Steel and Elford (1987a). Selection effects (range, antenna patterns etc.) have been removed, and the distribution normalized to the peak at ~105 km. Also shown, as a solid line, is the model calculated as described in section 2; input parameters were prf = 20 Hz and $V = 35$ km/sec. Except at low velocity (where $a_v$ is important) the total attenuation $a$ is dominated by the diffusion term $a_d$, due to the low prf; since $a_d$ does not depend upon the velocity (equation 6), the actual
The range limitation of 101 < R < 139 km results in the half-power, half-width ~1.5; as for the 54 MHz meteors, echoes are observed in the z = 33° lobes which have the height can then be deduced directly from the range. By transmitting a wide beam and then analysing only signals from ranges 101 < R < 139 km, any meteor echoes are observed in the vertical lobe, so that almost all meteors peaks well above 100 km, probably close to 110 km, and is strongly asymmetric with many more meteors detected in the 33° vertical lobe cause the error in point B (B is incorrectly assigned by the mini-computer as being meteors cause point A to be amplified; the sporadic-E reflections in the vertical lobe cause the error in point B (8 is at 93 km = 110-112 km x cos 33°). Point C appears anomalously low, but there is no apparent reason for this. The data at D show an upturn in the number of meteors: this is probably due to meteors which are really at h < 88 km causing echoes in the z = 50°7 beams and then having their heights incorrectly assigned.

4. Height distribution at 6 MHz

Our large receiving array has a row spacing of 100 yards, which is equivalent to about 0.61 km at 2 MHz or 1.93 km at 6 MHz. Connecting all dipoles to form a co-phased array, the antenna pattern at 6 MHz consists of nine grating lobes: one is vertical, four occur close to the cardinal points of the compass at z = 33°2, and four occur at the interstitial azimuths at z = 50°7. By transmitting a wide beam and then analysing only signals from ranges 101 < R < 139 km, any meteor echoes in the z = 50°7 lobes are ignored except for a few echoes from h < 88 km. There should be no meteor echoes from the vertical lobe, so that almost all meteors are observed in the z = 33°2 lobes which have half-power, half-width ~1.5; as for the 54 MHz meteors, the height can then be deduced directly from the range. The range limitation of 101 < R < 139 km results in the height distribution being determined only for 84 < h < 117 km. The limiting magnitude of our present 6 MHz system is M_V = -6, but this will be improved by the provision of a steerable transmitting array which is now under construction.

In Fig. 3 the 2015 meteors observed at the time of the Daytime Ariel and Zotter Perseids showers in 1986 June are shown: for more details see Elford and Olsson-Steel (1987). These two showers have velocities of -37 and -27 km/sec respectively, and V = 35 km/sec was used in the model, along with prf = 20 Hz. Due to this low prf the diffusion term a_V dominates the total attenuation for all velocities, and the precise value of V used in the model is not important. The model gives a reasonably good description of the trend of the data, predicting the peak at h = 105 km with the majority of the detected meteors being below 110 km (cf. the model of Milsom, 1985) even though most of the influx, according to equation (8), is above 110 km. The following points are worthy of comment:

(i) Points A and B are in error and have the same origin. Patches of evolving sporadic-E ionization at h = 110-112 km detected in the 33° vertical lobe are really at h < 88 km causing echoes in the z = 50°7 beams and incorrectly picked out by the mini-computer as being meteors cause point A to be amplified; the sporadic-E reflections in the vertical lobe cause the error in point B (8 is at 93 km = 110-112 km x cos 33°2).

(ii) Point C appears anomalously low, but there is no apparent reason for this.

(iii) The data at D show an upturn in the number of meteors: this is probably due to meteors which are really at h < 88 km causing echoes in the z = 50°7 beams and then having their heights incorrectly assigned.

(iv) Near E the low-altitude data underlie the model by about a factor of two.

5. Total meteoroidal influx to the Earth

Using our observed 2 MHz height distribution (as shown in Fig. 2) as a model for the true height distribution, Thomas et al. (1986, 1987) have analysed data from the Jindalee radar in order to estimate the total meteoroid influx to the Earth's atmosphere. More details of the radar are given by Thomas et al., but here we can mention that the system has a "mega-watt" transmitter separated by 150 km from an electronically steerable, 2.8 km long receiver array, and is fully tunable from 3-30 MHz. Meteors are detected at

Fig. 2. As for Fig. I except for meteors observed with a 2MHz radar; the majority of these were shower meteors detected in early May, late July and early August in 1985. Because the antenna spacing was more than /2, phase comparisons did not render the zenith angle (and hence height) unambiguously for some meteors, but this could be deduced with high confidence since the positions of the shower radiants are known. For details of the models (solid and dashed curves), see text.

![Diagram](image)

**WEIGHTED NUMBER OF METEORS**

- **x = UNAMBIGUOUS METEORS**
- **+ = AMBIGUOUS METEORS**

<table>
<thead>
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<th>WEIGHTED NUMBER OF METEORS</th>
</tr>
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<tr>
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</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.4</td>
</tr>
</tbody>
</table>

**HEIGHT DISTRIBUTION**

- 70 km
- 80 km
- 90 km
- 100 km
- 110 km
- 120 km
- 130 km
- 140 km

**ALL 2 MHz DATA, 1985**

- **x = UNAMBIGUOUS METEORS**
- **+ = AMBIGUOUS METEORS**

**HEIGHT DISTRIBUTION**

- N_T (72 < h < 105 km) = (h - 72) / 33 (10)
ranges out to several thousand kilometres via a number of different modes: direct backscatter, scatter via the F-region of the ionosphere and return along the same path, and a number of paths involving F-region and ground/sea reflections. Meteor echo rates of the order of five to ten per second are not unusual; an atmospheric collecting area of the order of 10^5 km^2 can be simultaneously monitored.

The meteor observations of Thomas et al. (1986, 1987) correspond to meteoroid masses in the range (2 x 10^{-7} < m < 8 x 10^{-6} g), so that for the first time there is substantial overlap between the masses observed by a meteor radar and by satellite detectors. The subsequent analysis by Thomas et al. renders a flux of particles of m > 10^{-6} g of 9 x 10^{-4} m^{-2} sec^{-1} and a mass exponent index α = -1.0, which is consistent with satellite data (Hughes, 1978; McDonnell, 1980; Laurence and Brownlee, 1986). This flux is about 30 times the previously-believed radar meteor flux, and implies an upward revision of the total solid-particle influx to the Earth (all masses from 10^{-7} g to 1 tonne) by about a factor of four to 16,000 tonnes per year (Thomas et al., 1986). The interpretation of the Jindalee data depends critically upon the input model height distribution, and requires a meteor component at high altitude (h > 110 km); these data therefore support our radical model for the true meteor height distribution. Although this model is extremely simplistic, we believe that it is at least a realistic basis for future work aimed at deducing the true characteristics of the meteoroid influx to the Earth's atmosphere. Clearly the results presented in this paper have important implications for the chemistry and dynamics of our atmosphere, the supply of meteoroids by comets and asteroids to the interplanetary complex, and the maintainance of the zodiacal dust cloud.

Acknowledgements

This work was largely supported by ARDS grant number B 8415432, and the University of Adelaide. Discussions with Dr. R.M. Thomas are gratefully acknowledged. During 1987 D.O-S. is European Space Agency Fellow at the Lund Observatory, Sweden.

References


DISCUSSION

Fechtig: Concerning the total influx of material to the Earth: Hughes gives for masses between $10^{-16}$ and $10^{-6}$ g a number of 44 tons per day. If one uses this number, your total mass would go up to approximately 60 tons per day!

Olsson-Steel: We must look at actual figures in more detail. Certainly the total influx is dominated by the $10^{-6}$ to $10^{-2}$ g meteoroids, from these observations.

Hajduk: How can you distinguish that you do not record ionospheric inhomogeneities instead of meteor echoes at 2 MHz and 140 km heights? Have you observed diurnal variation of echoes?

Olsson-Steel: It is a major problem that with a strong ionosphere the vast majority of echoes are from E-region ionization during the daytime. To avoid the problem we start observing at about 3 a.m. local solar time (when the E-region has died down) and must stop at sunrise (about 7 a.m. for these observations). Thus we cannot observe diurnal variations.

Hajduk: Because of a lower mass index of Eta Aquarids, the contribution of faint shower meteors should be negligible in comparison with the background rates.

Olsson-Steel: Our implementation of the 2 MHz system uses two identical beams pointed East and West. If the flux were predominantly due to the sporadic meteors at the times of observation, then the count rates in the two directions should in fact be the same, and this is not the case: by far the highest rates are found in the beam, in which the shower meteors are expected, confirming that most of the meteors detected are from the shower. Thus, we must conclude that the mass distribution index is in error, due to the selection effects described in this paper.
MASS DISTRIBUTION OF UNDERDENSE METEOR ECHOES: SELECTION OF BASIC DATA

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Volume of recorded underdense meteor echoes is determined by the transmitted power, threshold sensitivity of the receiver, antenna gain including its directivity and by the range of reflecting point on the meteor trail. These parameters must be considered when the mass-distribution index $s$ is evaluated.

In basic model of underdense meteor trail the incident radio wave is scattered by free electrons of ionized meteor path. These electrons oscillate freely and behave as if no other ones were present (McKinley, 1961). Upper limit for underdense electron line density $\alpha$ is sufficiently below the transitional value $\alpha_{tr} \approx 2.4 \times 10^{14}$ electrons/m (Kaiser and Closs, 1952). Using combine transmitting and receiving antenna and neglecting the formative stage of an underdense trail, the equation for received echo-power $P_r$ is

$$ P_r = \frac{P_T G_0 S}{32 \pi^2 R_0^2} A^2 \alpha^2, \text{ or, } P_r \sim \frac{S^2 \alpha^2}{R_0^3} $$

where $P_T$ is transmitted pulse power, $G_0$ is antenna power gain relative to an isotropic radiator, $S$ the antenna directivity in the direction to the reflecting point at the range $R_0$, $\lambda$ - wavelength, $r_e$ - classical electron radius.

The model for the number of particles $n$ having masses between $m$ and $m + dm$ has usually the form

$$ n \sim m^{-s} dm $$

Providing $\alpha \sim m$ and putting $P_r \sim A^2$, the integral or cumulative distribution of trails, $N$, having the electron line density or greater is then given by

$$ N \sim \alpha^{-(s-1)} $$

or, substituting for $\alpha$ from Eq. (1),

$$ N \sim \left[ R_0^{3/2} S^{-1} A \right]^{-(s-1)} $$

Equation (4) in logarithmic form represents a straight line of negative slope ($s-1$). In practice, the term $R_0^{3/2} S^{-1}$ is often considered a constant which leads to an inappropriate value of the mass-distribution index $s$ when all recorded underdense echoes are applied for the analysis.

According to Eq. (1) Fig. 1 shows the relation between line density, $\alpha$, and received echo amplitude $A$ with $SK^{-3/2}$, as a parameter. A similar diagram was already presented by McIntosh and Simek (1969). With the minimum value of $A$, echoes are recorded for line densities
between $\alpha_{\text{min}}$ and $\alpha_1$, where $\alpha_{\text{min}}$ corresponds to threshold sensitivity of the system ($P_{\text{min}}$) and $\alpha_{\text{max}}$ is maximum line density of an underdense trail having the echo amplitude $A_{\text{min}}$ sufficiently lower than the underdense-overdense cutoff. We do not reach usually $\alpha_{\text{max}}$ value having the amplitude $A_{\text{min}}$ because of the greater path loss and hence reduced equipment sensitivity at greater distances. Sensitivity factor $(SR^{-3/2})_{\text{max}}$ limits lower line density in the whole range of $\alpha$. The volume of all recorded underdense echoes is defined by $A_{\text{min}}$, $A_{\text{max}}$, $(SR^{-3/2})_1$, $\alpha_{\text{max}}$ and $(SR^{-3/2})_{\text{max}}$ where $A_{\text{max}}$ represents maximum amplitude of an underdense echo occurring in the region of $(SR^{-3/2})_{\text{max}}$ which, providing one discrete level, is reduced to one point (direction). Only in the same direction echo having $\alpha_{\text{min}}$ is observable.

We see that the number of echoes with $A > A_1$ is reduced by limiting value of $\alpha_{\text{max}}$. The range of equipment sensitivity $\Delta$ is a constant for $A_{\text{min}} \leq A \leq A_1$ and, therefore, we may use only echoes within boundaries $A_1$, $A_{\text{min}}$, $(SR^{-3/2})_1$, $(SR^{-3/2})_{\text{max}}$. All echoes having amplitudes $A > A_1$ and line densities $\alpha > \alpha_1$ must be discarded. By using line densities for the analysis, the range of applicable $\alpha$ is allocated within $(SR^{-3/2})_1$, $(SR^{-3/2})_{\text{max}}$. We are then losing the region of highest counts with $\alpha$ over the range of $\alpha_{\text{min}}$ to $\alpha_1$.

Such a procedure does not require the application of "meteor sensitivity contours" as described by Kaiser et al. (1966) and Poole et al. (1972).

Minimum range of recorded shower meteors depends on the radiant zenith angle. This must be taken in account when mass-distribution parameter for a meteor shower is to be determined. The observing period is then divided into series, say, 1-hour intervals and averaged normalized echo-counts (in %) are used for parameter's calculation according to Eq. (4).

References

1. Introduction

The extensive development of professional meteor programs after the second World War involving photographic, radar and image orthicon techniques added vastly to our knowledge of meteors. The Harvard Super-Schmidt program, which operated from February 1952 to January 1959, recorded some 6 000 doubly photographed meteors. About 2 800 orbits have been reduced to date. About 2 100 meteoroid orbits have been obtained in various small camera photographic programs carried out in the USA, Canada, Czechoslovakia, the USSR and elsewhere. A quantum jump in the number of available meteor orbits was obtained in the 1960's when several multi-station high-power meteor radar systems became operative. These stations recorded meteoroids down to approximately 8-10 magnitude. The total number of meteor orbits recorded by these stations is of the order of 70 000 or more.

Information on meteor orbits is widely scattered in the scientific literature and is often available only in publications with limited circulation. Information about individual radio meteor orbits has mainly been available as internal observatory listings or tapes. In the absence of key scientific personal much of this information was in the 1970's difficult to locate or even lost.

At the 1976 IAU General Assembly Commission 22 proposed that a meteor data center be established at the Lund Observatory for the collection of meteor observations by radio and photographic techniques. The decision was confirmed by the 1982 IAU General Assembly and a small sum was allocated for the support of the data center. The archived data are mainly two-station photographic orbits or multi-station radio orbits. Visual observations are not archived, since such programs do not provide precise orbital information.

The photographic data were originally punched on 80 column cards with two 80 column card images for each meteor. The first card image contains the identification no., time of appearance and orbital elements plus mass; the second card image contains identification no. and time plus geophysical/photometric data such as heights, velocities and magnitudes. Data formatting, references and other relevant information are documented in an information pamphlet which is available on request. The photographic data are now in the process of being converted to tape.

The major radio meteor programs (Harvard, Adelaide, Mogadisho, Obninsk and Kharkov) have each produced some 5 000-40 000 orbits. The Harvard Radio Meteor Project alone obtained in the period 1961-69 some 40 000 orbits. Owing to the vast amount of data individual orbits have as a rule not been published.

2. Photographic orbits

Table 1 summarizes the photographic orbit catalogues which presently are included (or in the near future will be included) in the IAU file. For a more detailed discussion of this data as well as detailed references see Lindblad (1971, 1987). We note that the number of available photographic meteor orbits is of the order of 5 000.

As detailed in Table 1, there is some overlap between the various catalogues. USSR meteor orbits are often reported in several places. The references given in Table 1 are judged to be the most complete. Orbital and geophysical/photometric data are often reported in separate publications, no doubt reflecting various stages in the data reduction process. Recently a very complete catalogue of the Odessa data has appeared (Kramer, Shestaka and Markina, 1986).

Results obtained by the Czechoslovakian and European camera networks have not yet been published in full. To date some 300 orbits have been reported by Ceplecha and co-workers in various numbers of Bull. Astron. Inst. Czechosl. and in SEAN Bull. (Smithson. Short-lived Event Alert Network Bull., Washington D.C.). Unfortunately the latter publication is seldom available in astronomical libraries. The Czechoslovakian data are of high precision and they represent a random sample obtained over a period of more than 35 years. (In contrast the Harvard Super-Schmidt data were mainly obtained in the three year period 1952-54). The publication in full of the Czechoslovakian meteor orbits is therefore eagerly awaited by the astronomical community.

A number of two-station photographic orbits have been obtained in various amateur programs. See reports by Nippon Meteor Soc. (1984), Ochiai (1985) and Betlem (1985). It is planned to include most of these orbits in the IAU file. The orbits have been obtained using short focus cameras, hence the precision of the data may be slightly lower than that obtained in the professional programs. A number of two-station TV-camera orbits have recently been published (Jones and Sarna 1985 and references therein). Also these orbits will later be included.

3. Radio orbits

Table 2 summarizes the major radio meteor orbit collections presently included in the IAU file. The column denoted "source" acknowledges the scientist or institute from which the present author has received the appropriate tape.
Table 1. List of photographic meteor orbit catalogues

<table>
<thead>
<tr>
<th>Station</th>
<th>Years</th>
<th>No. of orbits</th>
<th>Authors</th>
</tr>
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<tr>
<td>Harvard (Mass.)</td>
<td>1936-52</td>
<td>139 (144)</td>
<td>Whipple</td>
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<tr>
<td>&quot;</td>
<td>1951-52</td>
<td>27</td>
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<tr>
<td>&quot; (New Mex.)</td>
<td>1952-54</td>
<td>413</td>
<td>Jacchia and Whipple</td>
</tr>
<tr>
<td>&quot;</td>
<td>1952-54</td>
<td>313 (359)</td>
<td>Hawkins and Southworth</td>
</tr>
<tr>
<td>&quot;</td>
<td>1956-59</td>
<td>353</td>
<td>Posen and McCrosky</td>
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<tr>
<td>&quot;</td>
<td>1952-54</td>
<td>1790 (2529)</td>
<td>McCrosky and Posen (Graphical reduction)</td>
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<tr>
<td>Prairie Network</td>
<td>1963-75</td>
<td>336</td>
<td>McCrosky, Shao and Posen</td>
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<tr>
<td>MORP</td>
<td>1971-84</td>
<td>218</td>
<td>Halliday, Griffin and Blackwell (and unpubl.)</td>
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<tr>
<td>Dushanbe 1.</td>
<td>1940-55</td>
<td>73</td>
<td>Katasev</td>
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<td>1957-59</td>
<td>181</td>
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<td>1960-63</td>
<td>72</td>
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<td>&quot;</td>
<td>1964</td>
<td>77</td>
<td>Babadjanov et al.</td>
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<td>&quot;</td>
<td>1965-66</td>
<td>15 (18)</td>
<td>Babadjanov and Getman</td>
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<td>&quot;</td>
<td>1968-77</td>
<td>44</td>
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<td>&quot;</td>
<td>1966-67</td>
<td>20*</td>
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<td>Odessa 1.</td>
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<td>&quot;</td>
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<tr>
<td>&quot;</td>
<td>1961-65</td>
<td>122 (124)</td>
<td>Kramer and Markina</td>
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<td>1962-72</td>
<td>50</td>
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<td>1973-83</td>
<td>62*</td>
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<td>Kiev</td>
<td>1957-66</td>
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<td>1967-76</td>
<td>70*</td>
<td>Sherbaum et al.</td>
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<td>Ondrejov</td>
<td>1951-56</td>
<td>321*</td>
<td>Ceplecha et al.</td>
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* An asterisk indicates that the data are not yet included in the IAU file. A number in parentheses gives the total number of orbits listed in a catalogue (including overlapping catalogue data and/or later rejected orbits).

Table 2. List of radio meteor orbits

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<td>Kharkov</td>
<td>1975</td>
<td>Kharkov</td>
<td>5317</td>
<td>&quot;</td>
<td>B.L. Kaschev and A.A. Tkachuk, 1980, World Data Center B, Moscow.</td>
</tr>
</tbody>
</table>

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The Harvard Radio meteor project was initiated by F.L. Whipple with G.S. Hawkins and R.B. Southworth as principal investigators. The Data Center is indebted to the Director of the Harvard-Smithsonian Observatory forko distribution of the radio meteor data. The Adelaide survey was initiated by G. Elford with C. Nilsson and G. Gartrell as principal investigators. The Adelaide orbital data was retrieved through the efforts of D. Olsson-Steel and we are indebted to G. Elford for permission to distribute the data with the USSR radio orbits has been made available by the World Data Center B, Moscow.

4. Accuracy of catalogue data

In general it is difficult to assess the quality of data obtained at a particular station or by a particular investigator. An investigator may select only the best photographic images for analysis, or study a random sample of the data, or analyze the available data in full. In fireball-meteorite-recovery programs the emphasis is on reducing photographic trails of meteors with low terminal heights. In some studies the time of appearance of the meteor was not precisely recorded, and the mid-exposure time was used in computation with resulting loss of accuracy. Some investigators have included in their catalogues a measure of the relative accuracy of each orbit. This index is included in our records. When no index of relative accuracy was given, various other measures of orbital accuracy have been introduced. For a discussion see Lindblad (1973).

The early orbital calculations were in many cases done by hand or with desk calculators, in which case computational errors are not uncommon. Some errors or misprints in the published data have been corrected after correspondence with the original investigators. At the Data Center the published small camera meteor orbits have been checked for internal consistencies, i.e. do values of \( V \) and \( a \) agree? are values of \( e \) and \( e \) consistent, etc. These checks revealed numerous inconsistencies in the published orbital elements.

An independent study of the errors in the photographic orbital data has been made by Koseki (1986). A list of errors and corrections from this study is probably acceptable.

5. Data requests

Investigators have in the past asked for tapes, cards or listings of data. Since card readers are becoming obsolete in many countries, data will in the future be distributed on magnetic tape. The possibility of making the data available on diskettes is being studied. In the past many investigators have been rather specific in their requests - they are only interested in orbits from a particular stream, sporadic meteor orbits, etc. Such requests are welcomed, but since they may involve computer programming they can only be expedited with some delay and at cost.

Acknowledgements

The author is indebted to the scientists and institutes mentioned in the text for valuable help and to the IAU for financial support.

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Babadjanov, P.B. and Kramer, E.N.; Ionosphere and Meteors, Section V of IGY program, No. 12 (pp. 1102-124), Moscow, 1963.
Babadjanov, P.B. and Kramer, E.N.; Ionosphere and Meteors, Section V of IGY program, No. 12 (pp. 125-141), Moscow, 1963.
Betlem, H.; 1985, Radiant, 7, 73.
McCrosky, R.E., Shao, C.-Y. and Posen, A.; 1978, Meteoritics, 37, 44.
Ibadov: What do you think about using spacecraft (maybe in the future)?
Lindblad: To date there has not been devised a good instrument for obtaining meteoroid orbits in space. Such an instrument, if constructed in the future, should probably be based on a modified Sisyphus type of instrument, i.e. a four-telescope instrument observing the reflected light from a small interplanetary body.
The work describes briefly the application of the complete solution of the basic equations of meteoric physics, found in connection with solving the problems of photographic meteor theory, to the construction of theoretical Fresnel characteristics. It is shown how the meteoroid deceleration can be incorporated into concepts of radar physics. The corresponding equations are derived and the possibility of using these Fresnel characteristics for the evaluation of the ablation parameter and the 'pre-atmospheric' velocity from the registered amplitudes is briefly discussed.

The Fresnel characteristics are the tool for determining the velocities of radar meteors. The starting point for their construction must be the formula which would provide us with the power received after the reflection of radar-wave on the ionized trail. We will be dealing exclusively with the underdense type trails. Then, we can use the formula

\[ P_R = P_I \frac{G_T R^2 e^{\alpha L^2}}{16 \pi^2} \left( \int \frac{N_e}{R^2} \exp\left(\frac{i \pi \alpha L}{2} \right) dV_e \right)^2, \]

(e.g. Novikov et al., 1986). In the same paper the interested reader can find the concluding radar equation valid for the nondecelerating bodies

\[ P_R = P_I \frac{G_T G_R e^{\alpha L^2}}{32 \pi^2 R^3} \left( \int \frac{8 \pi^2 r^2}{\alpha} \exp\left(-\frac{8 \pi^2 r^2}{\alpha^2} \right) I^2 \right), \]

where

\[ I = \frac{1}{V^2} \int dV \exp \left[ -\lambda (x_0 - x) + \pi \chi^2 / 2 \right], \]

is the mathematical expression for Fresnel characteristics themselves. Because the behaviour of the characteristics is given only by \( I \), we will consider further only this quantity, where

\[ x_0 = 2v(t-t_0)/R_0, \quad \Delta = \beta^2 \delta R_0/(\chi \alpha^{3/2}). \]

The quantity \( t \) gives the time instant at which the body passes the specular point. The meteoroid velocity \( v \) and the ambipolar diffusion coefficient \( D \) obtained from \( I \) are related to the values of these quantities at the specular point of the trajectory, as well.

\( R_0 \) is the distance from this point to the observer. In the past the quantities we were used mainly for evaluating \( v \). But this is a quantity which must be converted to \( v_{\infty} \) (the pre-atmospheric velocity) to be able to determine correctly the heliocentric orbit of the parent meteoroid. The first attempt to use the fresnel characteristics for finding the \( v_{\infty} \), the ablation parameter \( c \) and the other parameters has probably been made by Kostylev and Kostylev (1980), Kostylev (1982) and Kostylev and Alferova (1985). But they did not use the exact physical theory. Therefore, after the new exact solution of the basic equations of meteor physics giving the distance \( I \) as a function of time \( t \), was published (see Pecina and Ceplecha, 1983, 1984), it seemed worth trying to incorporate this new concept also into the theory of Fresnel characteristics. In case of successful development of the theory we would be provided with the possibility to obtain the \( v_{\infty} \) and \( c \) directly from the characteristics.

We will now briefly describe the derivation of the desired formulae. The detailed derivation will probably be published in the Bulletin of the Astronomical Institutes of Czechoslovakia in 1988 under the title The derivation of Fresnel characteristics when the deceleration of the meteoroid is taken into account. We will only deal with the quantity analogic to \( I \) from equation (2). Let us consider the expression inside the absolute value sign in the equation (1) and denote it by

\[ X = \int \int \int \frac{N_e(r,t)}{R^2} \exp\left(\frac{i \pi \alpha R}{2} \right) dV_e. \]

One integration can be performed profiting from the fact that our problem is axisymmetrical and \( N_e \) depends only on the radial distance \( r \) from the axis, on the coordinate \( z \) (which increases in the direction of motion of the body and gives the position of the reflecting electron with respect to the specular point for which it equals to zero), and on the time \( t \), as well. Then we can re-write (3) in the following way:

\[ X = \int dz dV_e N_e(r,z,t) K(r,z), \]

where

\[ K = \frac{G_T G_R e^{\alpha L^2}}{32 \pi^2 R^3} \left( \int \frac{8 \pi^2 r^2}{\alpha} \exp\left(-\frac{8 \pi^2 r^2}{\alpha^2} \right) I^2 \right). \]
where

\[ K(r,z) = \frac{\exp\left(i \frac{kz^2}{2R^2}\right)}{R^2} \int d \phi. \]

The coordinate system used was described by Novikov et al. (1986). The sufficiently accurate result of the last integration reads

\[ (5) \quad K(r,z) = \frac{\exp\left(i \frac{kz^2}{2R^2}\right)}{2R^2} J_0(kr), \]

where \( J_0(x) \) is the Bessel function of zero order. Now, we must find the relation giving \( N_e \) if the deceleration of the body is considered. Solving the set of equations of meteor physics

\[ \begin{align*}
(6a) & \quad m \ddot{v} = -R S \dot{v}^2, \\
(6b) & \quad \dot{Q}_m = - \frac{1}{2} S v^3, \\
(6c) & \quad a = -a_0,
\end{align*} \]

we can arrive at the expression

\[ (7) \quad a(h) = \frac{2}{3} \frac{K m^{2/3}}{\mu} \int e^{-\dot{v}^2/3} \int (h) \dot{v}^2 e^\dot{v}^2/3, \]

where \( a = \frac{d}{(20 \mu)} \) is the ablation parameter and \( h \) stands for the height above the ground. To complete equation (7) we must add the relation getting the dependence of \( v \) on \( h \). But it has already been done by Pecina and Ceplecha (1984):

\[ \left[ E_i(\dot{v}^2/6) - E_i(\dot{v}^2/6) \right] F(h) = \left[ E_i(\dot{v}^2/6) - E_i(\dot{v}^2/6) \right] F(h), \]

where \( E_i(x) \) is the integral exponential function and

\[ F(h) = \int h \int (h) dh. \]

The quantity \( h \) can be related to the time \( t \) by the integral

\[ (9) \quad t = t_0 \int_0^h \frac{df}{v(f)}. \]

and the geometrical relation

\[ (10) \quad h = h_0 + 1 \cos z_R. \]

It is evident that \( l > 0 \) for \( h > h_0 \) and \( l < 0 \) for \( h < h_0 \). The distance \( l \) is measured along the meteor trajectory. So, we have obtained the expression of \( a(h) \) which takes into account the deceleration of the meteoroid. We have to solve the equation of diffusion. Its solution is given by the formula

\[ (11) \quad N_e(r,z,t) = \int \int G(\tau,\tau',t,t') \cdot Q_e(\tau,\tau') d\tau', \]

where the Green function of our problem has the form

\[ (12) \quad G(\tau,\tau',t,t') = \frac{\exp\left(-\frac{(x-x')^2+(y-y')^2}{4D(z)(t-t')}\right)}{4D(z)(t-t')} \]

and the source term \( Q_e \) is given by

\[ (13) \quad Q_e(r,t) = \frac{\exp\left(-\frac{r^2}{r_0^2}\right) \exp\left(-\frac{r^2}{r_0^2}\right) \int v(1) e^{1-z}, \]

(e.g., Novikov et al., 1986). We have considered the initial condition \( N_e(\tau,\tau,0) = 0 \). Inserting expressions (12) and (13) into (11) we get

\[ \int \int G(\tau,\tau',t,t') \cdot Q_e(\tau,\tau') d\tau' = \int \int \exp\left(-\frac{r^2}{r_0^2+4D(z)(t-t')}\right) \exp\left(-\frac{r^2}{r_0^2+4D(z)(t-t')}\right) d\tau', \]

where

\[ t_k = t_0 + \int_0^z \frac{df}{v(f)}. \]

Now, we can integrate equation (4) with respect to \( r \) and \( z \):

\[ (14) \quad x = \int_0^x dz \int_0^r N_e kr dz. \]

where we have used \( E_i(\frac{x}{2}) = \frac{n+2}{2} \int_0^x x e^{(x-2) \frac{x^2}{2}} \]

\[ \frac{1}{2} \int_0^x (x-2) e^{(x-2) \frac{x^2}{2}} \int_0^x (x-2) e^{(x-2) \frac{x^2}{2}} \]

\[ = 4(2\pi)^2 D(z) \int_0^x \frac{df}{v(f)} dx, \]

where we have used \( E_i(z) = 2v^n \) (see Kaschcheev et al., 1967). Using the dependence of the diffusion coefficient on \( z \) in the form
and realizing that the main contribution in the integral comes from the part of trajectory adjacent to \( z = 0 \), we obtain our final formulae (for the imaginary and real part) of the power received:

\[
I_1 = \sum_{i=1}^{n+2} \sin(z_i)^2 \int \frac{1}{2} \left( \frac{d^2 z}{dx^2} \right) dx - \sum_{i=1}^{n+2} \cos(z_i)^2 \int \frac{1}{2} \left( \frac{d^2 z}{dx^2} \right) dx.
\]

Then, the corresponding theoretical amplitude is computable from the formula

\[
A_i^T = c \sqrt{S_i^2 + C_i^2},
\]

where \( c \) is a normalizing constant into which all constants from equations (7), (12) and (13) were included. The index \( i \) labels the measured impulse in the characteristics. To find the required parameters we must apply a procedure ensuring the following constraint:

\[
\sum_{i=1}^{N} (A_i^M - A_i^T)^2 = \text{min},
\]

where \( A_i^M \) stands for the measured amplitude and \( N \) gives their number. Then, we must find the values of the following quantities: \( c, \ t_0, v_\infty, v_o, \alpha, h_j \). But we can avoid the necessity to find \( c \) if normalizing all amplitudes to the chosen one, say \( A_1 \). Further, it was revealed during the numerical experiments that it is better to compare squares of the normalized amplitudes. It means the satisfaction of the following condition:

\[
\sum_{i=2}^{N} \left[ (A_i^M)^2 - Q_i^T \right]^2 = \text{min},
\]

where

\[
Q_i^T = \frac{S_i^2 + C_i^2}{S_i^2 + C_i^2}.
\]

The method due to Hauck (1971) (designated usually as the method of gradients) was used to satisfy the condition (17). The formulae following from it are given in the Appendix. The method was tested on the following set of parameters: \( t_0 = 0.02422s, v_\infty = 60.00 \text{ kms}^{-1}, v_o = 59.50 \text{ kms}^{-1}, \alpha = 0.030 \text{ s}^2 \text{km}^{-2}, h_j = 97.62 \text{ km} \).

The following table lists the results obtained as a function of the relative accuracy with which the integrals entering the computation were performed as well as the CPU time needed on EC 1040 computer:

<table>
<thead>
<tr>
<th>( t_0 )</th>
<th>( v_\infty )</th>
<th>( v_o )</th>
<th>( \alpha )</th>
<th>( h_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02499</td>
<td>61.57</td>
<td>59.81</td>
<td>0.045</td>
<td>97.63</td>
</tr>
<tr>
<td>errors</td>
<td>0.00015</td>
<td>1.56</td>
<td>0.57</td>
<td>0.008</td>
</tr>
<tr>
<td>CPU time needed</td>
<td>39 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02426</td>
<td>61.41</td>
<td>59.73</td>
<td>0.037</td>
<td>97.61</td>
</tr>
<tr>
<td>errors</td>
<td>0.00012</td>
<td>1.30</td>
<td>0.47</td>
<td>0.006</td>
</tr>
<tr>
<td>CPU time needed</td>
<td>50 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02425</td>
<td>61.38</td>
<td>59.71</td>
<td>0.036</td>
<td>97.60</td>
</tr>
<tr>
<td>errors</td>
<td>0.00012</td>
<td>1.26</td>
<td>0.46</td>
<td>0.006</td>
</tr>
<tr>
<td>CPU time needed</td>
<td>69 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the light of the presented results I am convinced the method described can work and is worth further developing. We will then have at our disposal the method providing us with \( v_o \) and \( h_j \) in case of faint radar meteors with the sufficient accuracy for other reliable statistics.

The Appendix.
where \( l \leq k \leq 5 \), and

\[
M_{jk} = \sum_{i=2}^{N} a_{ij}^{T} \frac{2q_{i}^{T}}{2p_{k}}
\]

and

\[
P_{k} = \sum_{i=2}^{N} \left[ \frac{M_{ik}^{A}}{M_{i}} \right] \frac{2q_{i}^{T}}{2p_{k}}.
\]

The order of parameters used is listed in the table:

<table>
<thead>
<tr>
<th>j</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{j} )</td>
<td>( t_{0} )</td>
<td>( v_{\infty} )</td>
<td>( v_{0} )</td>
<td>( \varepsilon )</td>
<td>( h_{0} )</td>
</tr>
</tbody>
</table>

The iteration procedure starts with properly chosen parameters \( p_{j} \), \( t_{0} \), \( v_{\infty} \), \( h_{0} \), which were assumed to correspond to those following from the application of the old method relying on the observational material where the relation \( D_{03} = D_{0}(h_{0}) \) served as a tool for finding \( h_{0} \) if \( D \) is known.

\( D_{03} = 4.25 \text{ m}^{2} \text{s}^{-1} \) was employed, \( v_{0} = v - 0.5 \) and \( \varepsilon = 0.01 \text{ s}^{2} \text{km}^{-2} \) were used as other starting values. CIRA atmosphere (1972) was utilized. So, we had \( p_{j}^{\text{old}} \) with which the set of linear equations was solved. Then \( p_{j}^{\text{new}} = p_{j}^{\text{old}} + dp_{j} \) and \( p_{j}^{\text{new}} \) were substituted for \( p_{j}^{\text{old}} \) in the set of equations in question. This iteration loop was terminated unless \( |dp_{j}| \) was less than any prescribed value for \( j \). The sum of squared differences in sense of the condition (17) was assumed to decrease during the iteration procedure. If not, the iteration was terminated, as well. The derivatives needed were computed according to the following formulae:

\[
\frac{\partial q_{1}^{T}}{\partial p_{k}} = 20_{1}^{T}\left[ 8(\frac{2}{\alpha})^{2}D_{03} \frac{2q_{3}}{2p_{k}} F(h_{0}) e^{v_{1}^{2}/6} - 2F(h_{0}) e^{v_{1}^{2}/6} B_{1} \cos z_{R} l_{1} v_{1} \right] / |\text{Det}_{1}|
\]

and

\[
\frac{\partial q_{1}^{T}}{\partial p_{j}} = -40_{1}^{T} \frac{v_{j}}{v_{0}} e^{v_{0}^{2}/6} F(h_{0} - 1) \cos z_{R} l_{1} v_{1} / |\text{Det}_{1}|
\]

All derivatives in these formulae are to be computed in the explicit sense. The distances \( l_{i} \) were obtained by solving the transcendental equation (9) for corresponding time instants \( t_{i} \) related to \( \lambda_{M} \). \( v_{i} = v(l_{i}) \) was evaluated making use of the inverse to \( E_{i}(x) \), as described by Pecina (1986). The derivation of the formulae for \( \frac{\partial q_{1}^{T}}{\partial p_{k}} \) is tedious and was, therefore, left to the paper dealing with the detailed derivation of all formulae constituting the foundation of the described method.

REFERENCES


DISCUSSION

Olsson-Stael: This effect would be important as regards the derivation of heliocentric orbits even though the change in $V_{\infty}$ is quite small. How big is the change compared to the experimental uncertainties? Would this not be an even more significant effect for the few meteors detected by radar much lower? That is, closer to the point of maximum deceleration.

Pecina: I cannot say now, because I have presented a model computation. The full answer could be given when applying the theory to observations. But this will be made after the theory will be somewhat improved.
Double and multistation data on meteors from photographic and television records are used to derive relative and absolute numbers of sporadic meteoroids coming to the Earth's vicinity and their mass accession. Seven different meteoroid populations are dealt with separately inside the A-level, B-level, and C-level, with not too many sporadic meteoroids belonging to the Giacobini-Zinner comet shower. Between the A and C level meteors differ in their orbits partly in analogy to comet families and different groups among the C-level meteoroids: C1 with short-period elliptically-concentrated orbits, C2 with long-period randomly-inclined orbits, and C3 with short-period randomly-inclined orbits. C3 meteoroids are only small population among bigger bodies, but they become quite dominant for bodies with masses less than $10^7$ to $10^8$ grams. This knowledge comes from recent analyses of double-station meteor data obtained by TV cameras (Hawkes et al. 1984; Jones and Sarma, 1985; Sarma and Jones, 1985). The classification proved to be the same problem as for the brighter Super-Schmidt and small-camera meteors (Jones, 1995).

Thirty years ago, meteoroids coming to the Earth's vicinity were assumed to be approximatively of the same structure and composition. In the years 1965 and 1967, Verniani and Jacchia argued in favor of all meteoroids being low density (0.2 g/cm$^3$) friable bodies. This was based on their analyses of atmospheric trajectories of meteoroids photographed by Super-Schmidt cameras. This highly simplified view originated from biased statistical handling of the data (Cizek et al., 1988). Different meteoroid populations were first recognized even sooner, in 1958, and independently by Jacchia and Cizek, from systematic differences in meteor beginning heights. When the correct dependence of beginning height on velocity was applied to observations, several discrete levels of beginning heights were found (Cizek et al., 1988).

The survey of all known meteoroid populations is given in Table I. The two main levels separated by 10 km difference were denoted A the lower, and C the higher. Another 10 km higher than C level belongs to meteoroids originally denoted by Verniani and Jacchia as "asteroidal". The C level meteoroids differ in their orbits partly in analogy to comet families and different groups among the C-level meteoroids: C1 with short-period elliptically-concentrated orbits, C2 with long-period randomly-inclined orbits, and C3 with short-period randomly-inclined orbits.

### Table I

<table>
<thead>
<tr>
<th>Observational material</th>
<th>Television cameras</th>
<th>Super-Schmidt cameras</th>
<th>Small cameras</th>
<th>Fireball Network</th>
<th>Properties of the meteoroid material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2 \times 10^{-5}$ to $5 \times 10^{-2}$</td>
<td>$5 \times 10^{-4}$ to 1 g</td>
<td>$10^{-3}$ to $2 \times 10^{0}$</td>
<td>$2 \times 10^{0}$ to $2 \times 10^{7}$</td>
<td>$\gamma$, $\delta$, Assumed composition. Parent bodies</td>
</tr>
<tr>
<td>Group</td>
<td>Characteristic $a$</td>
<td>Characteristic $e$</td>
<td>Characteristic $i$</td>
<td>Characteristic $e$</td>
<td>Characteristic $i$</td>
</tr>
<tr>
<td>&quot;asteroidal meteoroids&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) ... semimajor axis, $e$ ... eccentricity, $i$ ... inclination, $\gamma$ ... bulk density of the meteoroid, $\sigma$ ... ablation coefficient, $K_{IP}$ ... relative observed numbers.
b) only one meteor Ro 011204060 recognized as "asteroidal"; its elements are given.
c) $\gamma$ corrected for random 1 (instead of 1.352) by adding the sun opposing part of C1 (IIIA) to C3.
different systems of cameras in regard to sensitivity. The most important tool in making a coherent picture of all data lies in superposition of the mass intervals of these 4 different sets of data, as you can easily check in Table 1.

The observational material used in this paper consists of 3624 sporadic meteors (561 sporadic fireballs: PH and EN fireballs), 812 sporadic small-camera meteors, 1848 Super-Schmidt sporadic meteor (McCrosky and Posen (1961), 403 TV sporadic meteors), which is practically all, and mostly published, of precise optical data on meteors available nowadays. The masses of individual meteoroids originate from integration of the whole light curve and except for the question of changes in luminous efficiency, masses are highly preferable over any estimates based only on one value of maximum brightness with some kind of average velocity, as is the case of interpretation of visual observations. Also radar data are severely limited in this respect.

Table 1 contains only survey of all meteoroid populations revealed so far. There is enough statistical material to study the mass distribution of individual groups in smaller mass steps. We used cumulative numbers of meteoroids and divided the whole interval of 12 orders in mass into small steps of 0.2 in log m. In one type of observational material the relative numbers of meteoroids belonging to individual groups are given directly by observations. We start with fireballs and used the cumulative number (McCrosky, 1969). In log N-log m plot for each group of meteoroids separately. The next observational material to fireballs belongs to the small-camera meteors. Their relative numbers, comparing the individual groups, are also given directly by observations. If we want now to join the cumulative-number plots of fireball groups and small-camera groups of meteors into one plot for each group, we are actually searching for one constant in logarithmic representation, which should hold for all small-camera groups to continue smoothly the fireball groups. The low sensitivity bias is well defined this way by the overlapping statistical distributions. This procedure can be used to join any of the other neighboring systems of data, small-camera with Super Schmidt meteors, and Super Schmidt with TV meteors. In all cases, one single value of the relative shift was found between the neighboring observational materials. The absolute calibration of the cumulative number curves was done by comparing the results on the type-I fireballs with the recent work of Halliday et al. (1984) on meteorite falls and deep penetrating fireballs. The slope of both independent analyses of cumulative numbers are identical in two digits (-0.69) and the difference in absolute terms yielded a small correction of the mass scale and of the absolute number of meteoroids.

\[
\log m \text{(this paper)} = \log m(\text{Halliday et al., 1984}) - 0.2 \\
= \log m(\text{Cephecha and McCrosky, 1976}) - 0.3
\]

The above described procedure gave also a perfect check on validity and consistency of our results based on much bigger observational material with the results of Halliday et al. (1984).

The results of all this computations are given in Table 2. The mass intervals are 0.2 in log m from 6.8 to 4.6 in logarithm of gram. For each meteor group separately, Table 2 contains logarithms of cumulative numbers already calibrated to the whole Earth’s surface per one year. In the last column, the logarithms of cumulative numbers are given for all sporadic meteoroids, as they resulted from summing the numbers of meteoroids of all groups inside each mass interval.

Table 3 contains incremental numbers as they resulted from Table 2. For each mass interval, Table 3 contains logarithms of numbers and also logarithms of masses inside each of the 0.2 wide logarithmic mass interval, for each sporadic meteor group separately. The last column gives the same for all sporadic meteors as it resulted from summing up incremental numbers and masses of all the meteor groups.

The results of Table 3 for all sporadic meteors are compared in Fig. 1 with “visual” data published by Hughes (1978). The absolute values in typically visual interval from 0.1 to 10 gram agree almost perfectly, but outside this interval the discrepancy is by orders of magnitude, and it is systematic and of opposite slope. I think that this only points out, how dangerous is any extrapolation of cumulative numbers beyond the region of actual full-sensitivity of a receptor. In case of interpretations of visual observations, more populated smaller bodies of high velocities are added to few bigger bodies of low velocities at the same maximum brightness, unresolved. This makes the cumulative slope seemingly steeper. We also compared our results with a model of meteoroid fluxes given by Grün et al. (1985) and based on lunar micro-cratering and Whipple’s (1967) interpretation of meteor statistics inside mass interval of 10⁻¹ to 10⁰ grams. The same order of discrepancy as with the Hughes values was found. Fig. 2 represents the comparison of our flux curve of all meteoroids with the flux curve of Grün et al. The average slope is identical between log m = 0.7 and log m = 1.3, which is a typical interval for the visual meteor observations (and close to SuperSchmidt sensitivity interval), on which the slope given by Whipple (1967) mostly depends. The dimension of a crater, when related to the mass of its projectile, has similar big spread due to velocity of the projectile as in the case of “maximum brightness of a visual meteor”. Again more populated smaller projectiles of high velocities are added to few bigger projectiles of low velocity at the same dimension of their craters.
Cumulative numbers $N$ of meteoroids of greater mass than $m$ (in grams). $N$ is given for the entire Earth's surface per year, a) the results of this paper, b) the flux model of Grün et al. (1985). The a) curve is extremely well defined for meteoroids with $\log m > -3$. The discrepancy or a) and b) at $\log m = -3$ is almost 2 orders of magnitude unresolved. This makes the cumulative slope seemingly steeper. The detailed knowledge of the meteoroid velocity and its changes during the meteoroid atmospheric trajectory in case of photographic and TV meteors makes the results of this paper on meteoroid fluxes and masses preferable over results of any indirect methods of mass determination based mostly on one experimental value (crater diameter or maximum brightness with the lack of velocity data).

From the results of this paper, the incremental mass has the absolute maximum at the largest mass boundary of our observational material and a local maximum just at the visual meteors (they are close to the SuperSchmidt meteors). This local maximum at $\log m = -0.5$ is mostly caused by the A-group bodies. They comprise a half of all meteors in the whole Super region and almost 90% at $\log m = -0.5$.

As a check on the problem of calibration of masses, an extreme and rather crude assumption on the luminous efficiency $T$ was also introduced. The results of this paper represented by curve a) in Fig. 1, are distinctly preferable to all so called "visual" or "visual-extrapolated" data and also over lunar cratering data with the following precautions:

The extreme wings below $\log m = -3$ and above $\log m = 5$ are close to the boundaries of the sensitivity of all the incorporated observational systems and may contain less bodies than is the reality. Inside the interval from $\log m = 5$ to $\log m = -3$ the incremental masses can differ from reality maximally by 10.3 in $\log m$, but the relative change from interval to the next interval is better than 0.1 in $\log m$. Finally the method of dividing the meteors into groups and handling them separately, gives better results than any procedure taking the meteors as only one statistical body.

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Fig. 2 represents the relative percentage change of three types of the meteor bodies expressed in incremental numbers:

a) the stony material
b) the A-group material (carbonaceous bodies)
:: the cometary material.

I think that most of internal discrepancies in results of studying meteorites by objective optical means in the past, originated just from the fact that we first learned about meteoroids from the mass interval of the complicated interlaced systems of meteor bodies.

And I finish the presentation of the paper by just one number more: the total influx of sporadic meteoroids, in the mass interval of 12 orders from $2 \times 10^{-9}$ grams to $2 \times 10^{-2}$ grams resulted in $3 \times 10^7$ g per year for the entire Earth's surface. And most of this mass is in the form of bigger meteoroids.

REFERENCES

DISCUSSION

Fechtig: I assume that the densities for your groups given in Table 1 are average numbers. Therefore you should give ranges to intercompare your results with, for example, densities for Hylleby dust.

Cephecha: Certainly, I can give the ranges of densities from the distribution of the values. The intervals of the densities in g/cm³ are:

"ast" + 1: 2.7 to 5.9
A + II : 1.4 to 2.7
B : 0.65 to 1.7
C + IIIA : 0.55 to 0.91
D + IIIIB : 0.18 to 0.38

These intervals contain two unseparable components superposed: the random errors of determination of the densities and the real distribution of bodies with different densities. Inside the given intervals of densities there lies 2/3 of the values, while 1/6 of the values is outside the interval at the upper end of the distribution and 1/6 is cut off at the lower end of the distribution.

Lindblad: In Table 1 there is a systematic difference between the mean orbital elements of photographically determined orbits and television cameras' orbits, in the sense that the former are smaller than the corresponding photographic orbits. Is this due to a difference in the mean mass, or what is the explanation?

Cephecha: This is due to the difference in the mass. The explanation lies most probably in much higher ejection velocities of smaller particles from the source, mainly from comets (Hawkes et al., 1984; Jones et al., 1985), which changes the orbits quite significantly.

Grön: The slope of the cumulative mass distribution of 0.6 to 0.7 seems very low, at least if it is compared with the slope of somewhat smaller particles derived from lunar microcraters (Grön et al., 1985).

Cephecha: The average cumulative slope of photographic, visual and microcrater counts of meteoroids are indetical in the mass range from 0.05 g to 5 g. For bigger bodies, the slope decreases to -0.69 in good agreement from three independent analyses (McCorky: 1968, Distribution of Large Meteoric Bodies, Smithsonian Astrophys. Spec. Rep. 280; Halliday et al., 1984; Cephecha, this paper). For bodies smaller than 0.05 g, the cumulative slope decreases to -0.9, which is held up to at least 0.001 g. The next two orders of smaller masses are too close to the lower boundary of the whole studied interval of 12 orders that the slope from 10⁻³ g to 10⁻⁴.6 g may be different from reality. In any case, between 10⁻³ to 10⁻⁶ g one would expect an increase of the slope again to fit the satellite data (if they do not reflect some denser system of Earth bound particles, because sporadic meteors used in this paper are strictly interplanetary). I repeat again that the advantage of photographic and IV meteors lies in detailed knowledge of velocity and mass at many points of each individual atmospheric trajectory.
Table 3
Incremental numbers and masses.
Logarithms of numbers, \( \log N \), and logarithms of total masses, \( \log M \), inside each mass interval of 0.2 in \( \log m \) are given. Units: \( m \) in grams, \( N \) ... numbers of meteoroids for the entire Earth's surface per year.

<table>
<thead>
<tr>
<th>mass interval ( \log m )</th>
<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
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<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
<th>( \log N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 - 0.4</td>
<td>2.22</td>
<td>8.92</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.4 - 0.6</td>
<td>2.73</td>
<td>8.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.6 - 0.8</td>
<td>2.55</td>
<td>8.25</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>0.8 - 1.0</td>
<td>2.55</td>
<td>8.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
ON THE INTERACTION METEOR COMPLEX

J. Rajchl
Astronomical Institute, Czechoslovak Academy of Sciences, 251 65 Ondřejov
Czechoslovakia

An approach to the problem of a meteoric complex called the Interaction Meteor Complex (IMC) is applied and discussed, where author’s former idea of the interaction layer (Rajchl 1969) is generalized. The role of an extended interaction of meteoroids is emphasized, both with planet surfaces and/or their satellites and with planetary atmospheres, elastic or inelastic in form. The dissipation and related formative aspect are joined in one complex and compared with a topological compact. Examples of all the above mentioned types of interaction are presented. In more detail the inelastic interaction with the Earth atmosphere of whole “spectrum” from faint meteors detected by TV technique to Fireball Network bolides, is considered. First results in the form of a structure and cross-complementarity are reported. The possibility of the existence of another “enlarged” structure is anticipated from topological aspects and supported for the outer planets of the Solar Planetary System by results of Levin and Simonenko (1982).

Introduction

As it is well known, the topological or geometrical approach, as compared with that represented by dynamical equations is considered as a more efficient one in the investigation of complex systems. On the other hand, it is the analogy which is the other method that shows very useful in this case. Finally, the relation between the dynamical and topological, or dissipative and formative aspects especially realized by the process of interaction may be of main interest. Such three axioms are used in our present approach to investigation of a meteor complex behaviour. Especially, the extension and generalization of author’s previous idea (Rajchl 1969) on an interaction layer ahead of a meteor body, mainly with accent on the interaction, is exploited. However, instead of atmospheric particles as projectiles and meteor bodies as targets, we consider the last ones as projectiles and planets with their environment in the form of their atmospheres or satellites, as targets. To decide whether the model used, together with achieved results are only superficial, or of some significance, we compared both the results and consequences with those of the mathematical topology itself.

Realization

At first, to distinguish the widely used “Meteor Complex” let us introduce the “Interaction Meteor Complex” (IMC). Compared with the former, IMC means rather its subset where the interaction of different meteor bodies with planets environment will be emphasized. The interaction may be of elastic and inelastic nature, and may be realized either with planetary atmosphere (soft) or with planetary body or its satellites (hard) in full analogy with the meteor interaction, where atmospheric projectiles interact either with meteroroid surface, or with its gaseous or dusty coma, respectively. Therefore, we consider formational and related formative aspects of interaction: elastic soft, elastic hard, inelastic soft and inelastic hard with possible consequences, examples of which follow: superrotation of upper atmosphere (i.e. faster rotation of the Earth atmosphere higher than 150km) by global deposition of meteoroids (Mitra 1974), “cosmogonical” influence of meteoroids on the planetary bodies rotation (Kiladze 1986), noctilucent clouds and enhanced airglow (Rajchl 1987) planetary rings and meteoritical craters. The remarked examples are meant as possible illustrations only and we concentrate in the present paper mainly on the case of the inelastic soft interaction. As has been shown (Rajchl 1987) some type of connection between meteoroids as sources and noctilucent clouds and enhanced airglow as responses might exist in the form called by present author the cross-complementarity. Let us now search whether similar or analogical connections may be real also for individual groups of IMC members.

Formerly, the present author (Rajchl 1959a, b) obtained - using the relation between heights and magnitudes in the meteor brightness maxima - that the dissipation intensity characterized by a factor \( \beta \) for both the sporadic and shower meteors 1) is higher for low together with high geocentric velocity meteors (i.e. \( v \approx 35\ km/s \) and \( v > 55\ km/s \)) than for those with velocity \( v = 35-55\ km/s \). 2) The different behaviour of meteors mentioned above and expressed in terms of the normal and abnormal (+) mean maximum brightness \( M \) shows an opposite or inverse nature for faint SS-meteors (i.e. photographed by Super-Schmidt cameras) relatively to the bright ones (NW/SC photographed by normal or small cameras). Therefore, by faint meteors the low and high velocity ones are - in average-normal \( B \approx -4 \) for fragmentation index \( \chi = 0 \) and the middle velocity meteors are more fragmenting.

To confirm these results, we enlarge the optically detected observational material used, on the whole, now attainable “spectrum” of meteors, i.e. from TV faint ones (Hawkes et al 1984) to very bright meteors, obviously, the main, widely known result of the soft interaction are the meteors alone/elastic and inelastic in real interaction is present simultaneously, but one of them is considered as prevalent/.
fireballs FN (McCrosky et al. 1977). Results are contained in Fig. 1, and Tab. 1.

Instead of the factor \( B \) and the fragmentation index \( \chi \), we used the mean maximum brightness \( M_m \) as a common characteristic of all meteor groups. Individual meteor groups (TV, SS ..., are characterized by \( \log M_m \), the mean photometrically determined masses. The values (points) for SS and NK/SC groups are accepted as starting and then optimized in combination with TV and FN values to define the crossover lines. The TV data show the largest deviation. From Fig. 1 we can see the above mentioned results as confirmed for the whole complex of meteor brightness used. Among all the groups the SS meteors show to be the nearest to the crossing point. It may be interesting to look for such "singular" meteors from the immediate neighbourhood of the inversion point. For example, the unusual spectrum of a meteor 0 mg, with beginning height 137 km (Cook et al. 1973) may be the possible candidate.

Let us call the results sub 1) shortly the \( \Psi \) structure (or more precisely \( \Psi \) and \( \Lambda \) or \( \Psi \) for mutually inverse behaviour as sub 2)) and the inverse connection between faint and bright meteors caused by the interaction with the Earth atmosphere, the cross-complementarity. Of some importance is, that the above results are valid also by showers: e.g. for Taurids, Geminids and Perseids, if we select those representing the three velocity groups (Rajchl 1959c) as for sporadics; faint Taurids and Perseids show the same behaviour as bright Geminids and vice versa. Furthermore, the bifurcation of Geminids (Ceplecha 1957) is especially emphasized, coinciding roughly with the double crossing point in Fig. 1. If we wish to explain the difference between normal and fragmenting groups as a result of their various perihelion distances, we must equally accept inversion for processes leading to such difference by faint and bright meteors (Rajchl 1974).

Comparison with topology

A question may arise whether such, at the first sight strange, results can be accepted as typical or even fundamental for a complex and thus for IMC. To substantiate our results we direct our attention to topology itself. Let us summarize these results in the following IMC hypothesis: the interaction of a flow (either in the form of meteor showers or in the more diffuse or "stochastic" form of sporadic meteors, or of some intermediate type) with a planetary environment leads to an interaction structure which is of a \( \Psi \) type. Connection between various groups of meteors (TV-FN) characterized by this interaction structure is of a type of the cross-complementarity. Both structures altogether are fundamentals of a IMC.

Now let us compare this hypothesis with topology: as it is well known, there exist a whole called the topological compact (or bi-compact) (Alexandrov 1977) and a structure analogous to our \( \Psi \) type—the so called Cantor discotinuum (CD) or Cantor triad (a whole transforms into combination \( ABA \cdots \)). Following Alexandrov we can roughly say that: if an infinite sequence of points of a topological space contains a subsequence convergent to some point of this space, or according to Peixoto (1962), if a motion of points is directed towards the so called un-wandered points, then a compact is here. This compact contains as a subset the CD and vice versa, the compact is a continuous picture of this CD. Therefore, if we now identify the sequence of moving points with our flow of meteoroids and the point of convergence with a planet (with its environment) we obtain that as a result of the flow-planet interaction something very analogous to the compact with its CD as subset, the IMC can arise. We may adopt the \( \Psi \) structure as a special type of structure isomorphic with the CD. Furthermore, using the ideas of Smale (1967), we can obtain a more general analog of our cross-complementarity in his hyperbolical sets, this is a fundamental type of connection with a very important property, well known also by CD: the crossing...

etc. of elements \( A, B \). Following Alexandrov we can roughly say that: if an infinite sequence of points of a topological space contains a subsequence convergent to some point of this space, or according to Peixoto (1962), if a motion of points is directed towards the so called un-wandered points, then a compact is here. This compact contains as a subset the CD and vice versa, the compact is a continuous picture of this CD. Therefore, if we now identify the sequence of moving points with our flow of meteoroids and the point of convergence with a planet (with its environment) we obtain that as a result of the flow-planet interaction something very analogous to the compact with its CD as subset, the IMC can arise. We may adopt the \( \Psi \) structure as a special type of structure isomorphic with the CD. Furthermore, using the ideas of Smale (1967), we can obtain a more general analog of our cross-complementarity in his hyperbolical sets, this is a fundamental type of connection with a very important property, well known also by CD: the crossing...
or the so called star-shape, directly as the analog of our \( \Psi \) type property, are reproducing at different scale levels! Therefore, we may conclude that our above mentioned results are not even in contradiction with the topological ones, but that further confrontation may be very fruitful.

**Generalization**

Till now we presented more detailed results of the interaction of meteoroids with the Earth atmosphere only. Now, we look for how it is by other planets of our Solar System from the point of view of all the above mentioned results. From the topological standpoint, for IMC as a compact the other planets can be also convergent points for meteor flows. As shown by e.g. Levin and Simonenko (1982) there exists a substantial difference between inner and outer planets in the planetocentric velocity range. From Tab. 2

<table>
<thead>
<tr>
<th>Planets &amp; Showers</th>
<th>Entry velocity of meteors into the atmosphere/from-to, in km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>10 - 85</td>
</tr>
<tr>
<td>Earth</td>
<td>11 - FLOW 73</td>
</tr>
<tr>
<td>Mars</td>
<td>5 - 58</td>
</tr>
<tr>
<td>Jupiter</td>
<td>QUASI 37-41</td>
</tr>
<tr>
<td>Saturn</td>
<td>22-26 SHOWERS</td>
</tr>
<tr>
<td>Uran</td>
<td>26-29 SHOWERS</td>
</tr>
<tr>
<td>Neptune</td>
<td>SHOWERS 36</td>
</tr>
<tr>
<td>Per</td>
<td>30-35 WERS</td>
</tr>
<tr>
<td>Gem</td>
<td>61</td>
</tr>
<tr>
<td>Tau</td>
<td>61</td>
</tr>
</tbody>
</table>

it is evident that whilst all the inner planets (without Mercury) have the entry velocities in the interval roughly 11-60 km/s, thus a very wide flow is in action, for outer planets it is not true. Here the flow of meteoroids is somewhat between the wide velocity range flow of inner planets and monovelocity meteor showers, i.e. something, what may be called the quasishowers. In other words, the sporadic or stochastic component is here larger than for showers, but smaller than by flows interacting with inner planets. Whilst, e.g. for a wide range velocity sporadic flow the \( \Psi \) structure is present and even if the condition

\[
\Delta = v^1 - v^II + v^III = 0
\]

is valid (where \( v^1 \), \( v^II \) and \( v^III \) are the mean velocities of the corresponding velocity groups from Tab. 1), the three-phase structures as special case of the \( \Psi \) structure may exist; by outer planets with quasishowers it is not valid. But, similarly as individual showers in summation can lead to something analogical to the known \( \Psi \) structure "in large", here the summation of individual quasishowers of all the four outer planets (see Tab. 2) together may lead to similar structure at still larger scale level. Thus, the \( \Psi \) structure is also apparent for a quasi-showers interaction, but for the outer planets as a whole on. However, many questions are still open here, e.g. detailed connection between quasi-showers and planetary rings compared to the main influence of dust particles on the planetary rotation in the past only for outer planets (Kiladze 1986). At first sight, it is obvious that the characteristic feature of the rings (just as that of meteor craters) is analogous to that of the CD-type. But, it seems that on the contrary to the velocity structures by the Earth, such ring structures similarly as e.g. the band structures by nortilucents clouds or enhanced airglow in the Earth atmosphere - are not results of the meteor interaction alone.

**Conclusion**

Summarizing, we may say that the main results in the form of the cross-complementarity and the \( \Psi \) structure, after a comparison with topological compact, show to be not only real, but of a fundamental importance. They constitute together with the main axiom of interaction the supporting blocks of the IMC. On the other hand, it is shown how can be expressed the relation and connection between dissipative and formative parts, or between dynamics and topology in meteor problems. The interaction layer region (between free-molecule and shock waves flows) seems to be very intimately connected with the crossing point region and/or with the crossing itself. Furthermore, several perspective extrapolations can be offered:

1) for meteor trains e.g. it follows that according to their low brightness (smaller than 0 mg), their velocity structure could be of the same type as for faint meteors (i.e. of the \( \Psi \) type);
2) according to the fundamental complementarity between faint and bright meteors and thus, according to some type of connectivity between them, the physical theory of both the categories of meteors should obey also some type of complementarity;
3) if the "reproduction" of the \( \Psi \) and cross-complementarity structures toward both the larger and smaller scale levels is true, then it may be a useful tool also in the more general cosmogonical considerations. In this respect connections to general solutions of the cubic equation (in velocities) related to the two basic factors \( A \) and \( B \), and to the Clifford algebra may be interesting.

**References**


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The meteor flares is a rather well-known phenomenon. Their appearance is usually connected with the process of the dividing of the body or a part of it into a large numbers of small fragments. From one to several flares with the duration 0.02-0.06 sec can have different meteors.

In this work only terminal flares, which lead to complete destruction of the meteor body, have been investigated, which is confirmed by the fact of sharp falling of the brightness right after the flare. And it is evident, that meteor bodies fragmentate into very small fragments otherwise, the presence of big particles would have prolonged the visible trajectories of meteors. This fact makes easy the estimation of the number of fragments, making it possible to consider them to be equal. This gives us the opportunity of using the simple physically clear model of fragmentation, offered by Levin (1956).

Let's put down the equation of luminescence, where I and i is accordingly the luminous intensity of meteor with fragmentation and evaporating simultaneously, the values $Q_f$ can be near to $q_f$, $A_f$ can be near to $A_f$. Then in the first approximation we can put down

$$n = (I_i/I_f)^3(\frac{Q_f}{A_f})^3$$

Then $n = (I_i/I_f)^3(\frac{Q_f}{A_f})^3$ for the terminal flare

$$(9) \quad n = (I_i/I_f)^3(\frac{Q_f}{A_f})^3$$

where index $f$ means the moment of the flare. Since during the flare the body is fragmentating and evaporating simultaneously, the values $Q_f$ can be near to $q_f$, $A_f$ can be near to $A_f$. Then in the first approximation we can put down

$$n = (I_i/I_f)^3$$

Using the formula (11) we can estimate $n$ with the help of the light curves of the meteors. The values $I_f$ are taken directly in the points of maximum of the luminescence of the flare. The values $I_f$ (the intensity which a meteor would have without fragmentation) can be calculated by the method as follows.

In works by Babadzhanov and Getman (1974, 1975) was picked out the class of non-fragmentating meteors of the Taurid stream, which were loosing their mass by intensive evaporation of atoms and molecules from the surface of the body. This was proved by the absence of wake and terminal blinding in the ordinary photographs and by the point structure of the images, obtained by the method of instantaneous exposure. It's well known, that during the evaporation of large meteor bodies the evaporating molecules and atoms are screening the surface of the body, giving strong influence at heat transfer to the body, which leads to the change of the coefficient $\Lambda_\alpha$.

According to works by Babadzhanov and Getman (1974, 1975), and by Bronshten (1983) $\Lambda_\alpha$ depends on the product $R_0 \rho_v^3$ ($R_0$ is radius of the body). Since $R_0 \gtrsim M^3$, we can make the substitutions $R_0 \approx M^3$ and $\rho_v \approx M^3$. In work by Babadzhanov and Getman (1975) (look also work by Bronshten (1983) was obtained the empiric dependence

$$\Lambda_\alpha = C(M^3 \rho v^3)^{\alpha}$$

For the part of trajectories from the height of the meteor appearance $H_m$ till the height of maximum light $H_m$ were obtained the constants

$$\log C = -5.75, \alpha = 0.5.$$
considering $p = p_0 \exp(-H/H^*)$ ($H^*$ is atmospheric scale height), $dt = -dH/v \cos Z$ (Z is zenith angle of the meteor radiant), $\alpha = 0.5$, let's integrate (13)

$$W^2 = W^* = \frac{A C H \rho^*}{2(\gamma^* - \rho_b) H^*} \gamma^2,$$

where $\rho_0$ is atmospheric density of the meteor appearance $H_0$, index $\gamma^*$ refers to the initial values velocity and mass of the meteor body, Putting (12) considering $\alpha = 0.5$ into the luminous equation

$$i = i_0 \frac{2 \gamma^2}{2 \gamma^2 - \gamma^4}$$

and considering (14) we'll get

$$i = B \rho^* \gamma^2 \left[ W^2 - N (\rho^* \gamma^2 - \rho_b \gamma^2) \right],$$

where $B = \frac{A C \gamma^*}{4(\gamma^* - 2)}$, $N = \frac{A C \gamma^*}{2(\gamma^* - 2) \rho_0}$. 

Using the formula (16) we can define the value $i^*$ in any point of the part of the trajectory from $H_b$ to $H_0$. If necessary we can turn to the magnitudes $m_b$ and $m_f$, according to $m = -2.5 \lg i^*$. 

Four meteors with the terminal flares, which have been photographed from two stations in Dushanbe (Babadzhanov and others 1966, 1968) have been investigated. With the formulas (16) and (11) were found the values $i^*$ and $m^*$. The following values of the constants have been used: $\lg \gamma^* = -19.0$, $\beta = 0.3 \text{ g/cm}^2$, $A = 1.21$, $H = 6.5 \text{ km}$. The values of the $\rho_0$ are taken from CIRA 1972.

The results of the calculation and some other data are given in the following table. The editorial symbols: $i_0$ is the observed luminous intensity at the height of the meteor appearance, $r_o$ is radius of fragment.

Table.

<table>
<thead>
<tr>
<th>No.</th>
<th>621234</th>
<th>632725</th>
<th>641623</th>
<th>641701b</th>
</tr>
</thead>
<tbody>
<tr>
<td>v(km/s)</td>
<td>19.0</td>
<td>64.5</td>
<td>24.6</td>
<td>24.0</td>
</tr>
<tr>
<td>$i_f$</td>
<td>6.9</td>
<td>398.0</td>
<td>1.7 \times 10^3</td>
<td>75.8</td>
</tr>
<tr>
<td>$i_b$</td>
<td>0.4</td>
<td>6.3</td>
<td>6.9</td>
<td>1.9</td>
</tr>
<tr>
<td>$i_f$</td>
<td>0.66</td>
<td>27.0</td>
<td>8.1</td>
<td>1.4</td>
</tr>
<tr>
<td>n</td>
<td>10^3</td>
<td>3 \times 10^3</td>
<td>9 \times 10^6</td>
<td>1.6 \times 10^5</td>
</tr>
<tr>
<td>$M_b$ (g)</td>
<td>10^{-3}</td>
<td>3 \times 10^{-4}</td>
<td>1.3 \times 10^{-5}</td>
<td>1.7 \times 10^{-5}</td>
</tr>
<tr>
<td>$r_o$ (cm)</td>
<td>4 \times 10^2</td>
<td>3 \times 10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
</tr>
</tbody>
</table>

From the results come out two important consequences:

- a) For three meteors out of four 621234, 641623 and 641701b the values $i_f$ can be compared with the values $i_b$, that is for the estimation of $m^*$ can be used the following: $n = (i_f/i_b)^3$;

- b) In case of evaporation of meteor bodies, the light curve goes up slowly (Figure) $|dm/dH| \approx 1/12$,

i.e. during the process of evaporation "m" changes not much. Let's reminded that the classic light curve (not considering the effect of block up, $\Lambda = \text{const}$) is $|dm/dH| = 1/6$.

The values $r_o$, obtained in this paper, coincide with the data of Simonenko (1967), who was inclined to conclude, that particles of a size of the order of $10^{-2} \text{ cm}$ appear to be structural elements (or grains) of meteor bodies.

![Fig. Light curves of meteors accordingly: observed (solid lines) and calculated by formula (16) (broken lines). Meteor's numbers from the above: 632725, 641623, 641701b, 6414623. The problem of flares is waiting for its decision. Its new aspect opens in connection with Levin and Bronsten's (1986) supposition about the analogy between the Tunguska body explosion and terminal flares and fireballs. To the author's mind these phenomena are of the same nature, but different scale. REFERENCES]


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PHOTOGRAPHIC DATA OF EXTREME PRECISION EVALUATED BY EXACT SINGLE-BODY SOLUTION OF METEOR PHYSICS

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2) Astronomical Institute of the ČSAV, 251 65 Ondřejov Observatory, CSSR

The exact solution of the single-body motion and ablation of a meteoroid in the atmosphere is applied to one of the most precise double-station records of a fireball photographed from Dushanbe Oct 30, 1962. The entire trajectory of 5.2 seconds duration from 77 km to 36 km of height with 258 time marks corresponds to a single value of the ablation coefficient.

1. Observational material

One of the most precise set of geometrical data on meteor atmospheric trajectory was derived for a double-station photograph of a fireball at Dushanbe, USSR, Oct 30, 1962, 17\textsuperscript{h} 26\textsuperscript{m} 19\textsuperscript{a} 07 (Babadzhanov, Getman, 1980). The entire photographed trajectory of this fireball contains 258 measurable time-marks spaced by 0.0202 seconds each and covering the height interval from 77.43 to 36.24 km. The maximum absolute brightness reached -7.3 magnitudes at 49.6 km. At each time-mark the observations yielded the relative time, \( t_0 \) and the height, \( h_0 \).

The standard deviation of one measured \( h_0 \) is ±1 meter, which is much better than the precision induced to observations by the theoretical model based on "flat Earth surface" (assumption of constant inclination of the trajectory to the surface: standard deviation - 19 meters). The 258 measurable time-marks occupy a time interval of 5.1914 seconds.

2. Theoretical model

The exact solution of the differential equations of the single-body theory was recently found by Pecina and Ceplecha (1983, 1984) in the form

\[
\begin{align*}
\frac{d}{dt} & \left( \frac{\mathbf{r}^2}{2} \right) - \frac{\mathbf{v}^2}{2} = - \int \rho \, dh \\
- \frac{d}{dt} & \left( \frac{\mathbf{v}^2}{2} \right) = - \int \rho \, dh \cos \zeta_R,
\end{align*}
\]

(1)

where \( \mathbf{r} = \int u^{-1} \exp(u) \, du \) is the exponential integral and

\[
\begin{align*}
\mathbf{r} & = \frac{1}{t} \int v^{-1} \, dt, \\
\mathbf{v} & = \frac{1}{t_0} \int v^{-1} \, dt,
\end{align*}
\]

(2)

where \( t \) is the time (independent variable), \( \mathbf{r} \) the distance along the trajectory, \( \mathbf{v} \) the velocity, \( h \) the height, \( \rho \) the air density, all of them at any given arbitrary point. The constant \( \zeta_R \) is the zenith distance of the radiant resulting from a linear least-squares correlation of \( h_0 \) and \( t_0 \).

\[
\begin{align*}
\frac{d}{dt} & \left( \frac{\mathbf{r}^2}{2} \right) - \frac{\mathbf{v}^2}{2} = - \int \rho \, dh \\
- \frac{d}{dt} & \left( \frac{\mathbf{v}^2}{2} \right) = - \int \rho \, dh \cos \zeta_R,
\end{align*}
\]

(3)

where \( c \) is the same constant as in equation (1). The parameters of the problem are: \( t_0 \), which defines the zero point of the relative time counting; \( l \) the distance along the trajectory at time \( t \); \( v \) the velocity at time \( t \); \( v_0 \) the initial velocity \( (t \rightarrow -\infty) \); \( \sigma \), the Ablation coefficient

\[
\sigma = \frac{A}{2 \mu} 
\]

(5)

where \( A \) is the heat-transfer coefficient, \( \mu \) the drag coefficient and \( \sigma \) the energy necessary for ablation of the unit mass of a meteoroid.

The solution of equations (1) and (2), with \( c \) and \( \cos \zeta_R \) derived from (3) and (4) can be performed by method of gradients of the four unknown parameters \( l_0 \), \( \mathbf{v} \), \( v_0 \), \( \sigma \). The velocity \( \mathbf{v} \) at any arbitrary point is defined by the same parameters from the velocity integral of the single-body equations:

\[
\begin{align*}
\frac{d}{dt} & \left( \frac{\mathbf{r}^2}{2} \right) - \frac{\mathbf{v}^2}{2} = \frac{2}{\mu} \frac{C}{\rho} \int \rho \, dh \\
\end{align*}
\]

(6)

where \( K \) is the shape-density coefficient

\[
K = \frac{A^2}{2 \mu} 
\]

(7)

\( \rho \), the bulk density of the meteoroid, \( A \) the shape factor

\[
A = \frac{5}{2} m^{-2/3} \rho^{-1/3} d^{2/3} 
\]

\[
\begin{align*}
\sigma & = \frac{K}{2 \mu} \\
m & \text{the meteoroid mass at an arbitrary point,} \\
m_0 & \text{the initial meteoroid mass (} t \rightarrow -\infty \text{)} \\
d & \text{the head cross-section of the meteoroid.}
\end{align*}
\]
The numerical procedure compares $l$ computed from (1) and (2) with $Q_{bs}$ and finds linear gradients of the four unknown parameters $l$, $v$, $w$, $\phi$ so as to approach condition (4). Thus starting with a first suitable approximation of these four values, each step in the direction of the gradient of these values goes toward the final solution, where the linear gradient of the four parameters is equal zero. At this point, the condition (4) is also fulfilled and the least-squares fit of (1) and (2) to $l$ is found. The partial derivatives necessary for solution of the gradient of the parameters are rather complicated expressions, but they can be straightforwardly numerically computed.

The value of $K_{m_0^{1/3}}$ resulted as 0.079 cm$^2$/g. With $\rho_0 = 3.7$ g/cm$^3$, $K = 0.5$ and the initial "dynamic" mass $m_d = 250$ g, which leads to the terminal mass $m_E = 31$ g. (CIRA 72 November atmosphere).

REFERENCES


3. Results

We applied the theoretical model of chapter 2 to the observational material described in chapter 1. We used CIRA 72 October and November atmosphere for the Dushanbe latitude as the air density model. The results follow:

a) The entire trajectory of the fireball can be expressed by one single constant value of ablation coefficient:

$$\varphi = 0.0300 \pm 0.0003 \text{ s}^2/\text{km}^2 \text{ for CIRA 72 October atmosphere}$$

$$\varphi = 0.0275 \pm 0.0003 \text{ s}^2/\text{km}^2 \text{ for CIRA 72 November atmosphere}$$

b) There are only 4 points amongst 258, which deviate in $l$ slightly more than 3 standard deviations from $l_{bs}$. (About 1 such value is expected under the normal distribution).

c) The two successive values of $l$ deviating by more than 3 standard deviations at $t = 4.33$ seconds indicate some breakage of the meteor body.

d) The resulting standard deviation for one observed $l$ from (1) and (2) resulted as -15 meters, slightly less than -19 meters, which had been computed on assumption of constancy of $z_R$ (flat Earth's surface) from equation (4).

e) The initial velocity resulted with precision better than -1 m/s:

$$v_{w0} = 13.6303 \pm 0.0009 \text{ km/s for CIRA 72 October atmosphere}$$

$$v_{w0} = 13.6340 \pm 0.0009 \text{ km/s for CIRA 72 November atmosphere}$$

f) The velocity changed during the entire trajectory from 13.61 to 5.85 km/s. The only method known to handle such a velocity change with not loosing more than 90% of the accuracy inhibited in the observations, is the method of Pecina and Ceplecha (1983, 1984) briefly described in chapter 2.

g) The deceleration changes from -0.035 km/s$^2$ at the beginning point to -4.08 km/s$^2$ at the maximum-deceleration point ($t = 4.73$ s at a height of 38.4 km) and back again to -3.65 km/s$^2$ at the terminal point. (CIRA 72 November atmosphere).
SOME NEW ASPECTS IN THE POSITIONAL REDUCTION OF
THE PHOTOGRAPHS TAKEN BY FISH-EYE OBJECTIVES

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Astronomical Institute of the Czechoslovak Academy of Sciences,
251 65 Ondřejov, ČSSR

In this work the method used up to now for a positional reductions of the photo-
graphs is compared with other reductional formulas. It was found that the reduction
formula presently used for determination of the zenith distance is suitable, howe-
er the formula for determination of the azimuth can be replaced by a new expression,
which essentially improves the total positional reduction.

The cameras with Fish-eye objectives (Opt-
ton - Distagon, f = 30 mm, a field of view
of 180°, focal ratio 1/3,5) are used in the
Czech part of the European Network for fire-
balls already more than ten years with a
great success.

Reduction of the photographs taken by ca-
meras with Fish-eye objectives consists in
the finding of the most suitable unknown
parameters of the interpolation formulas
describing the dependence of the azimuth and
the zenith distance on the measured rectangu-
lar coordinates.

For this purpose a certain number of sui-
table stars (usually about 15) is chosen on
the photographic plate as far as possible in
a near environment of a meteor. The equato-
rial coordinates of stars are known from a
catalogue. We have to transform these coordi-
nates to the horizontal coordinates - the
azimuth and the zenith distance. This way
we obtain theoretical coordinates \( \alpha^* \) and
\( \varphi^* \). From a measuring instrument we receive
rectangular coordinates \( x \) and \( y \).

Now we need to find the most suitable inter-
polation formulas between measured rec-
tangular coordinates \( x \) and \( y \), and a horizontal
coordinate system \( \alpha^* \) and \( \varphi^* \). Coordin-
ates \( x^* \) and \( y^* \) are computed values from
interpolation formulas. A solution of these
formulas must fulfill the requirement that the
sum of squared differences, \( \sum (\alpha^* - \alpha)^2 \)
and \( \sum (\varphi^* - \varphi)^2 \), is minimum for all stars
used.

Interpolation formula hitherto used for
determination of the azimuth is
\[
\alpha^* = \alpha_0 + \arctg \left( \frac{y^* - y_0}{x^* - x_0} \right)
\]  
(1)

where \( \alpha_0 \), \( x_0 \), and \( y_0 \) are small unknown parameters.

For determination of the zenith distance
formula
\[
\varphi^* = \varphi_0 - S \exp (D \varphi_1)
\]  
(2)

is used, where \( \varphi_0 \), \( S \), and \( D \) are unknown param-
eters. For \( \varphi_1 \) we have
\[
\varphi_1^2 = (\varphi - x_0)^2 + (y - y_0)^2
\]  
(3)

We must determine seven unknown parameters
in the common solution. The whole method of solu-
tion of the above mentioned interpolation
formulas is described in detail in Ceplecha

The interpolation formulas (1) and (2)
were compared, along with some other inter-
polation formulas, and the results are pre-
presented in Table 1 and 2. This comparison was
performed for one specially chosen case (as
large as possible range of zenith distances
and azimuths of measured stars).

We can see from Table 1 that the last
three interpolation formulas give better re-
results (represented by the standard deviation
\( \sigma \) ) than all the rest tested formulas, but
in the interpolation formula (2) we must
determine lesser number of unknown param-
ters. Therefore the interpolation formula (2)
is most suitable for use. The formula (1)
was used for determination of the unknown
parameters \( \beta \) and \( \gamma \) (the relation (3)),
which are necessary for interpolations for-
formulas in Table 1.

It is evident from Table 2 that the relation
\[
\alpha^* = \alpha_0 + \arctg \left( \frac{y^* - y_0}{x^* - x_0} \right) + B \left( \frac{y^* - y_0}{x^* - x_0} \right)^2
\]  
(4)

gives essentially better results than the
hitherto used formula \( A, B, \alpha_0, x_0, y_0 \)
are unknown parameters). The following for-
rmula from Table 2 gives rather better results,
but at the cost of the determination of more
unknown parameters.

In the end the best formulas (2) and (4)
were tested together for ten casually chosen
examples. From Table 3 it is evident that
in all cases we achieved the improvement of
the total reduction (represented by the
standard deviation \( \sigma \) ) and this improvement
makes about 15% on the average.

Conclusion

For next reductions of photographs taken
by Fish-eye objectives it will be suitable
to replace the hitherto used interpolation
formula for determination of the azimuth (1)
by the new formula (4) and to keep the inter-
polation formula (2).

REFERENCES

Vol. 38, No 4 (in print).
List of used symbols

- $\alpha_{\text{cat}}$: theoretical value of azimuth
- $\varphi_{\text{cat}}$: theoretical value of zenith distance
- $\alpha_{\text{com}}$: computed value of azimuth
- $\varphi_{\text{com}}$: computed value of zenith distance
- $x_i, y_i$: measured rectangular coordinates
- $a_0, x_0, y_0, \Delta, \theta, \psi$: unknown parameters in interpolation formulas for determination of the azimuth
- $U, V, S, D, T$: unknown parameters in interpolation formulas for determination of the zenith distance

\[ \Delta \alpha_i = (\alpha_{\text{cat}} - \alpha_{\text{com}}) \]
\[ \Delta \varphi_i = (\varphi_{\text{cat}} - \varphi_{\text{com}}) \]
\[ \nu = \frac{y_i}{x_i} \]
\[ u = \frac{x_i - x_0}{y_i - y_0} \]
\[ \sigma_a = \sqrt{\frac{\sum (\Delta \alpha_i)^2}{n - k_a}} \]
\[ \sigma_{\text{tot}} = \sqrt{\frac{\sum ((\Delta \alpha_i)^2 + (\Delta \varphi_i)^2)}{2n - (k_a + k_z)}} \]

\[ n \] number of stars
\[ k_a \] number of unknown parameters in interpolation formulas for determination of the azimuth
\[ k_z \] number of unknown parameters in interpolation formulas for determination of the zenith distance

All values of standard deviations are in degrees.

<table>
<thead>
<tr>
<th>$\sum (\Delta \alpha_i)^2$</th>
<th>$\sigma_a$</th>
<th>$\sigma_{\text{tot}}$</th>
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<tr>
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<td>0.00318</td>
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</table>

TABLE 1

Reduction formula

- $\sin(z_i/2) = U + Vr_i$
- $\sin(z_i/2) = U + Vr_i + Sr_i^2 + Or_i^3$
- $\sin(z_i/2) = U + Vr_i + Sr_i^2 + Or_i^3 + Tr_i^4$
- $\sin(z_i/2) = U + Vr_i + Sexp(Or_i)$
- $z_i = U + Vr_i + Sr_i^2 + Or_i^3$
- $z_i = U + Vr_i + Sr_i^2 + Or_i^3 + Tr_i^4$
- $z_i = U + Vr_i + Sexp(Or_i)$
- $z_i = U + Vr_i + Tr_i^2 + Sexp(Or_i)$

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### TABLE 2

<table>
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<th>Reduction formula</th>
<th>$\Sigma (\Delta a_i)^2$</th>
<th>$\sigma_a$</th>
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<td>$a_i = a_0 + \text{arctg}(u)$</td>
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<td>0.0262</td>
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<td>$a_i = a_0 + \text{arctg}(Av + Bv^2 + Cv^3)$</td>
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<td>$a_i = a_0 + \text{arctg}(Au + Bu^2 + Cu^3)$</td>
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### TABLE 3

<table>
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<th>$\sigma_z^\text{old}$</th>
<th>$\sigma_z^\text{new}$</th>
<th>$\sigma_{\text{tot}}^\text{old}$</th>
<th>$\sigma_{\text{tot}}^\text{new}$</th>
<th>improvement in $\sigma_{\text{tot}}$ in %</th>
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INTERPLANETARY DUST
1. Introduction

Attempts to derive the three-dimensional (3D) distribution of the zodiacal dust cloud from optical observations have been made since many years starting with models involving some scale height above the ecliptic plane or density distributions like the so called "Fan-models" (Divari, 1967). The problem of all these assumptions was the fact, that the observed intensity at the position of an observer is not exclusively related to the number density n of dust particles along the line of sight but also to the angular dependence of the scattering function (differential scattering cross section) of the dust particles. Therefore it was expected that infrared observations relating on the isotropic thermal emission of the dust particles would avoid these difficulties and lead more easily to realistic modelling of the 3D distribution of interplanetary dust. Unfortunately, however, the wavelength dependent index of refraction and also the size enters the calculations of thermal balance and temperature. This can lead to considerable deviations from the temperature predicted for a black body. Therefore, either extended calculations using Mie-theory (spherical particles!) have been performed taking into account the wavelength dependence of available indices of refraction (e.g. Lamy, 1974; Mukai and Mukai, 1973; Roesser and Staude, 1978; Schwehm and Rohde, 1977) or reasonable assumptions were adopted about average efficiencies of absorption in the visible or in the infrared, respectively, as pioneered for example by Kaiser 1976. From this it becomes evident that also infrared data are not a king's way to obtain easily the distribution of dust in the solar system. Nevertheless, recent results obtained by rocket experiments (ZIP: Zodiacal Infrared Project, Murdock and Price, 1965) and by the IRAS satellite (Hauser et al., 1984) are a source of information which is extremely important, since it relies on a different physical process. Another completely different physical aspect which also helps to solve the problem is a thorough analysis of the dynamics of meteoroids and especially micrometeoroids using data obtained from earthbased and space measurements. While these will be treated by other papers in this volume, the present review is restricted to the optical ad infrared point of view.

From admittedly very preliminary statements of infrared investigators one can get the impression that the IR results are generally consistent with previously determined interplanetary dust distributions (Hauser et al., 1984) and that the out-of-plane measurements are well matched with a dust density distribution (Murdock and Price, 1965) which is very similar to the Fan-model trend of distributions. The authors of this paper, are aware, that such models are only representing the crude overall shape of the cloud and that any details need more thorough and complicated modelling. A first step into details has been performed from the infrared groups by deriving the plane of symmetry of the zodiacal cloud from annual variation of the zodiacal infrared emission (Hauser and Houck, 1986; Good et al., 1986; Deul and Wostencroft, 1987) and to compare it with the results of observations in the optical range. This led to some agreement and also corroborated the findings of optical analysis (Misono, 1980; Schuerman, 1980) that the "plane" of symmetry is eventually warped. Another problem area, where infrared results seem to strengthen previous suspicions is the inhomogeneous composition of the interplanetary dust cloud. Simple optical models have been usually based on the assumptions that the physical properties of the dust particles are independent of location and that the number density decreases with solar distance according to a power law. These assumptions are made in order to manage the problem, to derive dust densities or to "invert the brightness integral" (Dumont 1973; Lamy and Perrin, 1986) in nontrivial cases. Nevertheless all investigators, including the authors of this paper, are aware, that such assumptions are suspect from physical reasons since there are processes (radiation, sputtering, packing effects) changing the dust particles while they are spiraling into the inner parts of the solar system due to the Poynting-Robertson-effect (cf. Fechtig 1984; Mukai und Fechtig, 1983). There has been also evidence from analysis of optical (Schuerman, 1980) and infrared observations that particle properties (e.g. Albedo, Dumont and Levasseur-Regourd, 1986) are changing and that the number density does not follow a simple power law (Hong, 1987). On the other hand Leinert et al. 1981 have shown, that with the exception of polarization the results of HELIOS 1 and 2 are surprisingly consistent with what would be expected from the two assumptions.
mentioned above. Therefore such simplified models are still justified as an initial step of approach, especially in the regions inside 1AU.

In the following sections we shall first present the geometric definitions and draw attention to some bewildering differences of terminology in the recent IR-literature. Then we adopt the most simple model approach referred to above and compare models suggested by optical observations of the zodiacal light with those proposed by infrared investigators. Finally some comments are presented towards the current and future discussion about more realistic models involving spatial changes of the dust properties.

2. Basic Geometry

As mentioned above, the symmetry plane of the zodiacal cloud and the ecliptic plane are not identical. However, for the following discussion the inclination between these planes (< 3°) is negligible although it plays an important role under other aspects (e.g., dynamics). We shall therefore make no distinction between the ecliptic, the invariable, and the symmetry plane unless it is explicitly mentioned. Under this precaution Fig.1 illustrates the problem and defines the geometric relations referred to in the text. An observer located at O at the solar distance R in the symmetry plane looks in the direction of his line of sight LOS and receives radiation scattered or emitted at an angle $\theta$ within his viewing cone (solid angle $d\Omega$). The particles of volume element $dV$ at P are illuminated by the Sun $S$, where $r$ is the distance of P from the Sun. The lower portion of each example presents the isodensity lines for $n=2n_\odot$, $0.5n_\odot$, and $0.25n_\odot$, respectively, as drawn in the $xz$-plane (heliocentric meridian). It should be kept in mind, that these isodensity lines are representing isodensity surfaces due to rotational symmetry about z in the 3D case. The lower portion of each example presents the deviation (in %) of each zodiacal light as predicted model from observational tables of Levasseur-Regourd and Dumont, 1980. Positive values indicate that the values predicted by the model are too bright and vice versa. The model calculations were performed using Leinert's method. The upper portion of each case presents in the upper portion of each case. These isodensity lines are representing isodensity surfaces due to rotational symmetry about z in the 3D case. The lower portion of each example presents the deviation (in %) of each zodiacal light as predicted model from observational tables of Levasseur-Regourd and Dumont, 1980. Positive values indicate that the values predicted by the model are too bright and vice versa. The model calculations were performed using Leinert's method. The upper portion of each case presents isodensity lines for $n=2n_\odot$, $0.5n_\odot$, and $0.25n_\odot$, respectively.

Unfortunately these definitions are not unambiguously used in the recent literature. While e.g. Frazier, 1977; Giese et al. 1985; Leinert, 1978 follow the definitions referred in Fig.1, the IR papers Murdock and Price, 1985 or Good et al., 1986 prefer cylindrical coordinates, i.e., and obviously the projection $r \cdot \cos(\beta)$ of $r$ on the symmetry plane. This undisturbed free choice of the authors turns out to become misleading if followed by statements such as "this functional form is a generalization of that used by Frazier" (Good et al., 1986) or by an inconsistent set of formulae after referring to Leinert, 1975 (Murdock and Price, 1985, Eq.(9) through (13)). A confusion of the definition of $r$ has only small influence on the results obtained from IRAS and the rocket project ZIP which both are performed at R=1AU and at large (> 30°) elongations. The ambiguity of definitions can however become fatal as soon as investigations are extended towards the regions near the Sun ($\Delta r < 1$). Another source of possible confusion is the difference in the definition of elongation as used in this paper and other zodiacal light work and the "elongation" measured in the symmetry plane (i.e., $\lambda-\lambda_\odot$) referred to in the papers of the IRAS and of the ZIP teams. Therefore care is necessary in comparing results and interpretations.

3. Simple 3D-Models

Most simple models of the 3D distribution of interplanetary particle number density $n(P)$ are based on the assumption of separability $n$ into one factor depending on $r$ only and another factor depending on $\beta_\odot$. Furthermore a power law is adopted for the dependence on $r$. This leads to $n(r,\beta_\odot)=n_0(r/\text{AU})^\delta(\beta_\odot)$ where $n_0$ is the particle number density at the earth orbit (1AU) while $r$ and $\beta_\odot$ are defined in Fig.1. Examples of such models are reviewed and extensively discussed elsewhere (Giese and Kinatider, 1986; Giese et al., 1986). Within the scope of the present paper it is sufficient to restrict the models derived from optical observations to some markedly different examples and to compare them with models derived from IRAS or ZIP data by the infrared investigators. Fig.2 presents in the upper portion of each case the isodensity lines for $n=2n_\odot$, $0.5n_\odot$, and $0.25n_\odot$, respectively, as drawn in the $xz$-plane (heliocentric meridian). It should be kept in mind, that these isodensity lines are representing isodensity surfaces due to rotational symmetry about z in the 3D case. The lower portion of each example presents the deviation (in %) of each zodiacal light as predicted model from observational tables of Levasseur-Regourd and Dumont, 1980. Positive values indicate that the values predicted by the model are too bright and vice versa. The model calculations were performed using Leinert's method. The upper portion of each case presents isodensity lines for $n=2n_\odot$, $0.5n_\odot$, and $0.25n_\odot$, respectively.
Fig. 2: Isodensity lines and deviation from optical observations for 30 distributions. Explanation see text.
as derived by the authors (Lamy and Perrin, 1986) was adopted. Fig.3 shows the scattering functions normalized to 0=90° for comparison. The value of n was adjusted in our calculations to obtain agreement with the observational tables at 90° of elongation in the symmetry plane. The circles in Fig.2 present circles of the same latitude \( \beta \) above the symmetry plane as seen from the observer, e.g. the outer circle represents the symmetry plane (ecliptic plane, \( \beta=0 \)), the center of the circles the (ecliptic) pole. The radial lines are the projections of meridians at different longitudes \( \lambda \) with respect to the Sun (left corner: solar direction).

**Fig. 3: Scattering Functions \( \alpha(0) \):**


The Fan-Model

\[
(1) \quad n = n_0 (r/AU)^{\nu} \exp(-\gamma |\sin \beta_0|)
\]

with \( \nu=1.3 \) and \( \gamma=2.1 \) presents the Fan-model as adopted by Leinert et al., 1981 and referred to by many investigators (Fig.2a). It achieves an excellent fit (mostly better than 10%) in the regions towards the Sun but is very poor in reproducing the brightness at high latitudes \( \beta > 60° \) and at the pole (deviation > 30%). A much better fit at the pole and in the circle \( \lambda=90° \) perpendicular to the heliocentric meridian can be achieved by an "Ellipsoid-Model" as shown by Dumont 1976 and Kinateder 1984 or in an equivalent way by a "Flattened Fan-Model" with \( \gamma=2.9 \) as shown by Fig.2 and Table I of Giese et al., 1986. In both cases, however, this has to be paid by a poor fit (typical -25%) in the heliocentric meridian towards the Sun at medium latitudes \( \beta \). From reasons discussed in detail in the mentioned paper a much better overall fit of the brightness in the optical range can be achieved by models, having some bulge above the Sun as suggested orally by Dumont at the IAU Assembly in Grenoble ("Sombrero-Model") or by a paper of Lumme and Bowell, 1985. Fig.2b shows a version of a Sombrero-type model proposed by Rittich 1986, based on the expression

\[
(2) \quad n = n_0 (r/AU)^{-1.3} (0.2 + 0.8 \cos 4\beta_0)
\]

dealt with called "Cosine-Model". As can be seen this model approximates the observations in all directions shown in the lower part of Fig.2b within about 10%. Therefore this quality of approximation is achievable with simple models which means, that models producing deviations of the order of, say 25%, have definitely to be rejected as unacceptable even within the rather modest scope of this section.

Recently Lamy and Perrin (1986) derived an unified functional approach to brightness and polarization data from the literature and obtained from this a 3D distribution of interplanetary dust and a corresponding scattering function by inversion of the brightness integral using the methods of Leinert et al. (1976) and Dumont (1973). They conclude that in the case of a power law values as \( \nu=1.3 \) are incompatible with the observational data and propose a density distribution

\[
(3) \quad n = n_0 (r/AU)^{-1.3} \cdot \exp(-3.5|\sin \beta_0| - 0.775 + 0.624 \sin \beta_0)
\]

which is shown in Fig. 2c. The corresponding scattering function derived by the authors from observations at 1AU is presented in Fig. 3 for comparison. Using this scattering function and Equ.(3) we computed the brightness distribution predicted by the model to compare with the observational data (Fig.2c). As can be seen, the brightness values fit in the symmetry plane very well but deviate at ecliptic latitudes \( \beta > 30° \) markedly (about -15 to -30%) from the Tables of Levasseur-Regourd and Dumont, 1980.

3D distribution derived from IR measurements are shown in Fig. 2d through Fig. 2f. Most investigators arrive close to an \( 1/r \) dependence of \( n \) in the symmetry plane while the IR balloon measurements of Salama et al. (1987) seems to be compatible with a classical Fan-model \( (\nu=1.3 \) and \( \gamma \approx 2.1 \) i.e. Leinert's model). A Fan-model with \( \nu=1.3 \) and \( \gamma=2.7 \) is shown in Fig. 2d. Using Leinert's scattering function this model provides in the visual range an excellent (3%) fit at the pole and an acceptable (better than about 15%) approximation of optical data all over the sky except in the region towards the Sun \( (\lambda<30°, \beta<60°) \), where the deviations become unacceptable (-25%). This is not surprising, since this model corresponds closely to a "Flattened Fan-model" as shown by Giese et al., 1986 which shares this disadvantages with the Ellipsoid-model of Dumont, 1976. It is, however, at least encouraging that this type
Fig. 4: Isodensity lines $n = 0.5 n_0$ perpendicular to the symmetry plane for
LN Fan-model: $v = 1.3, \gamma = 2.1$ Leinert et al. 1981; RI Cosine-model
Rittich 1986; LP Lamy and Perrin 1986; DG Good et al. 1986; MP Murdock
and Price 1985; FF Fan-model: $v = 1.1, \gamma = 2.7$. 
of Fan-models, which is proposed in a modification also on the basis of IRAS data (O'Call and Wolstencroft, 1987). It does not lead to unacceptable differences with respect to optical brightness at larger (\( \theta > 70^\circ \)) elongations.

From the papers of the IRAS team it is not clear that their \( \theta \) is the heliocentric distance (e.g., Hauser, 1976) or its projection on the symmetry plane. In the latter case the expressions \( \theta \) and \( \frac{z}{r} \theta \) in the paper of Good et al., 1986 ("cylindrical coordinates") would correspond in our terminology to \( r \cdot \cos \theta \) and \( \tan \theta \), respectively, if we adopt that in the model of Good et al., 1986.

The corresponding isodensity lines are shown in Fig. 2e and the deviations of the zodiacal brightness predicted by the model using Leinert's scattering functions are shown in the lower portion at the figure. The compatibility with the visual observation is moderate but acceptable (typical better than 20%) for elongations \( \theta > 70^\circ \) i.e. in the regions where the IRAS data come from. The model would however completely fail to present the solar hemisphere \( \theta < 50^\circ \) reaching deviations up to 55% at \( \theta = 30^\circ \) in the helioecliptic meridian. This would even become worse if Good et al., 1986 used the projection for \( r \), since in this case the density would become lower close to the Sun. On the other hand at large elongations (IRAS) the isodensity lines crossed by the LOS are practically the same for both cases \( r \) or \( r \cdot \cos \theta \), respectively, yielding the same quality of approximation of the visual brightness as in Fig. 2e.

Finally we compare the model of Murdock and Price (1985) with visual data. Since due to several misprints the formulae in the original paper are confusing we asked the authors who kindly provided us with the correct formula (Price, 1986). It is in the terminology of this paper.

The corresponding isodensity lines are shown in Fig. 2f. Using the Legendre-Polynomial approximation of the scattering function (Fig.3) published by the authors we arrive at unacceptable deviations in nearly all parts of the sky reaching even 133% at \( \beta = 30^\circ \) in the helioecliptic meridian. This is due to the unusually strong increase of the adopted scattering function. Therefore we did the same calculation using the more conservative scattering function of Leinert. In this case an acceptable agreement with optical observations can be achieved, except in the region of \( \lambda - \lambda^*, <50^\circ \) and especially close to the Sun (50%).

4. Discussion

In Fig. 4 the isodensity lines \( n = 0.5n_0 \) are compared for the models referred to above. It is interesting to note that for viewing directions corresponding approximately to the scanning cones of IRAS \( 50^\circ \leq \theta \leq 120^\circ \) the isodensity lines of the best optical model (RL, Cosine-model of Rittich, 1986), of the ellipsoid model (not shown here), and of the models suggested by IR investigations (FF Flattened Fan-model, GD Good et al., 1986, MP Murdock and Price, 1985) are close together. This explains the passable compatibility of the models derived from IR measurements with the visual data (Dumont and Levasseur-Regourd, 1980) in this region of the sky. On the other hand it is understandable from their low or steep decrease of \( n \) with \( \theta \) that Leinert's Fan-model (LN) or the model of Lamy and Perrin (LP) produce too high or too low brightness at large ecliptic latitudes, respectively.

For further discussion it is necessary to estimate how the relative contributions of the volume elements at different locations (P) along the LOS depend on the relevant wavelength. To simplify the problem we shall restrict ourselves to grey bodies and to particles which are large or at least not small compared to the wavelength. This is justified as a first step, since the particles mainly contributing to the zodiacal light are in the size range of radii between 10 and 100 \( \mu m \) (Giese and Grün, 1976; Röser and Staudte, 1978). Furthermore admitting grey and not just black bodies allows to take into account spatial variations of physical particle properties at least in terms of an albedo depending on location.

As has been shown by many authors (cf. Leinert, 1975) the observable spectral surface brightness \( F_\lambda \) at 1 AU of the zodiacal light (\( Wm^{-2}m^{-2}sr^{-1} \)) can be found by integration along the LOS in the visible region as

\[
\int \frac{\sigma(\theta) n(\theta)}{(r/AU)^2} \, d\theta
\]

Here \( F_\lambda \) is the solar flux (\( Wm^{-2} \)) at 1 AU, \( n \) the number density of dust particles (\( 1/m^3 \)), \( \sigma \) the differential scattering cross section (\( m^2/\text{ster} \)) per particle, and \( d\theta \) a line element along the LOS. In order to keep the problem as simple as possible and only to demonstrate the physical principles we will handle it as if there would be just one particle size. If discussion has to be extended to the case of a size distribution, \( \sigma \) can be understood as the average scattering cross section of one particle of the mixture (cf. Leinert, 1975).

In a similar way the spectral surface brightness due to thermal emission of the grains in the IR region may be found (cf. Peterson, 1963) as

\[
\int n(\theta) \rho(\lambda, T) \, d\theta
\]
Here $C$ is the cross section for absorption at the wavelength considered, which also can be substituted by an average cross section per particle for mixtures. $B(\lambda, T)$ is the Planck function (Wm$^{-2}$sr$^{-1}$).

From this it is evident, that the contribution to $I$ of a volume element at the position $P(r)$ per unit length along the LOS is governed by

$$(8) \quad VES = \left(\frac{F_{0} n(\theta)}{(r/AU)^{2}}\right) \cdot A \cdot (r/AU)^{-v}$$

which will be called hereafter (cf. Dumont and Levasseur-Regourd 1986) the volume elemental scattered intensity (VES). In the thermal region we use a corresponding expression

$$(9) \quad VET = n \cdot C_{abs} \cdot B(\lambda, T)$$

which we call the volume elemental thermal emission (VET).

During the following discussion we adopt further simplifications. For particles large compared to the wavelength having the geometric cross section $G$ and an Albedo $A$ we assume for the differential scattering cross section $\sigma = A \cdot G / 4\pi$ (isotropic scattering) and for the cross section of absorption $C_{abs} = (1-A) \cdot G$. Further we adopt $n_{R} = n_{abs} (r/AU)^{-v} f(B_{s})$ as in the previous section. Then we obtain

$$(10) \quad VES = \left[\frac{F_{0} n(\theta)}{4\pi} f(B_{s})\right] \cdot A \cdot (r/AU)^{-v+2}$$

and

$$(11) \quad VET = n_{0} f(B_{s}) \cdot (1-A) \cdot (r/AU)^{-v} B(\lambda, T)$$

It should be kept in mind that $B(\lambda, T)$ is a function of solar distance $r$. For a black or grey body thermal balance yields $T = 2800K \cdot r$ (e.g. Leinert, 1975).

Now we can compare VES or VET at a solar distance $r$ with the contributions (VES) and (VET) at $r=1AU$. In the symmetry plane ($f(B_{s}) = 1$) we obtain as an example with $\nu = 1 \cdot (n^{1.7}r)$ and an albedo $A = 0.1$ the relative values $\text{VES} = \text{VES}(\nu)$ and $\text{VET} = \text{VET}(\nu)$ as shown for different wavelength regions in Table I.

The strongest contributions per unit length of the LOS to the observed spectral brightness stem from the inner regions of the solar system and the contributions decrease systematically with increasing $r$. This is true for both, the visual region ($\lambda = 0.5\mu m$), where practically all brightness is due to scattered light (VES) and the IR domain ($\lambda = 5\mu m$) where the thermal emission (VET) is dominating. However, in the short wave range of the IR ($\lambda = 5\mu m$) the contributions of the hot dust inside 0.5 AU are extremely preferred, while at larger wavelengths ($\lambda > 20\mu m$) the contributions of the inner and outer regions are not as drastically different. Although VES (here $r$) is due to a quite different process the contributions of dust to the integral along the LOS are biased in the visible light in a similar way as in the infrared domain between 10 to 25 $\mu m$. Roughly spoken: The observer sees, within the limits of our model, the same dust. Also from this point of view the relative compatibility of the published density distributions is understandable.

Up to now we did not take into account any spatial change of the particle albedo (Lumme and Bowell, 1985; Fechtig, 1984). As has been shown by Giese and Kinateder 1986 a change of $A$ according to a power law $A = A_{0} \cdot (r/AU)^{-2}$ leads from a volume scattering function $n(r) \sim r^{-1}$ to a density distribution $n \sim r^{-v}$ with $v = 1 - v_{t}$, and to flatter looking 3D distributions (see their Fig.9). A decrease of Albedo $A$ or increase of absorption $(1-A)$ with increasing $r$ has been found from IR data by Dumont and Levasseur-Regourd 1986. They arrive at a density decrease close to $n \sim r^{-1}$ or $v = 1$. With the HELIOS result $v = 1.3$ we obtain correspondingly $\nu = 0.3 \cdot 0.9 = A_{0} \cdot (r/AU)^{-2}$. This would not too drastically modify the values of Table I. For example we obtain with $A = 0.1 (r/AU)^{-2}$ and $\lambda = 0.5\mu m$ at $r = 0.5AU$ or 2.5AU VES values of 9.8 or 0.09, respectively. For $\lambda = 20\mu m$ the relative thermal contributions $\text{VET} = \text{VET}(\nu)$ at r=0.5AU or 2.5AU about 4.1 or 0.09, respectively.

5. Conclusions

The 3D distributions of dust particle densities obtained from IRAS and ZIP data are in acceptable but not in good agreement with distributions derived from the zodiacal light. This is also true for the relative intensity distribution of zodiacal light as predicted from the IR models in viewing directions at larger ($\epsilon > 70^\circ$) elongations. At low elongations ($\epsilon < 40^\circ$) the density distributions proposed from IR investigations are incompatible with the visual data, while Sombrero type models are in satisfying agreement with visual observations. More thorough investigations are necessary including the regions close to the Sun and the near IR. These efforts have also to take into account with increasing complexity non grey bodies and spatial changes of the physical properties of interplanetary dust.
References


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DISCUSSION

Ibidov: It was very interesting. What is the minimal heliocentric distance up to which the power law for the number density of interplanetary dust holds?

Giese: The approximation by a power law seems to be valid even surprisingly close to the Sun. Helios penetrating to 0.3 AU and crossing with its line of sight regions close to 0.1 AU did not show evidence of a dust free zone. On the other hand, the raise of density cannot go on in the same way inside 10 to 3 solar radii. There is evidence for evaporation processes in these regions from IR measurements and theoretical calculations. In addition we found that the polarization of the F-corona would be much higher than the observed inside 10 solar radii, if the power law could be extrapolated into this region.

Gün: The radial dependence of the spatial density has to be stronger than \( n \propto 1/r \) - which would require no source of zodiacal particles at and inside 1 AU. As I have shown in my paper at this meeting (TS-2) collision provide the major source to zodiacal particles at 1 AU. Therefore a dependence \( n \propto r^{1} \) with \( r > 1 \) is required.

Giese: The isodensity lines for \( r = 0.8 \) shown in one slide were an exaggerated example, how \( n \) would change in the case of a hypothetical albedo variation \( \propto 0.5 \). Personally, I completely agree with you expecting an albedo effect, which might bring down \( r \) from 1.3 closer to one, but still with \( r > 1 \).

Babadzhanov: What do you think about sources of interplanetary dust? Does the distribution of dust correspond to the distribution of orbital inclinations of comets or asteroids?

Giese: The most probable inclinations inferred by Hang's integral from \( f(\beta) \) are of the order of \( i = 10^\circ \) to \( 15^\circ \) depending on the model. We are, however, hesitating at the present state to relate our results directly to the inclination distributions of asteroids or comets. The following paper by B. Kneissel will explain this in more details.

Disson-Steel: Isn't the problem of inverting the scattered-light data basically the same as the computer-applied tomography? Has anyone tried applying the C.A.T. algorithms to this problem?

Giese: This is a very interesting problem we also started to think about. In computer tomography there is the X-ray source and opposite to it a series of sensors each measuring the integral of absorption of all volume elements (voxels) along the ray from source to sensor. This whole system can be turned around the patient to obtain many crossing lines of sight and a system of equations to solve for the density of each voxel. In application to our problem there are two differences. We are not observing in forward scattering (extinction) and we have not the choice of an optimum geometry for the location of the sensors, especially without an out-of-ecliptic spacecraft photometer. However, it would be interesting to modify the method. A first step towards this was done by one short paper of a Spanish group and by the thorough application of their method of nodes of lesser uncertainty by Dumont and Levasseur-Regourd.
THE DYNAMICS OF THE ZODIACAL DUST CLOUD ON ACCOUNT OF OPTICAL AND INFRARED OBSERVATIONS

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The method to determine the inclination distribution of zodiacal particle orbits according to 3D-density models of zodiacal dust presented by Giese and Kneiβel (1987, this volume) is briefly discussed. The results show that models with additional bulges at the solar poles bear an isotropic component of the inclination distribution amounting up to 20% of all orbits, whereas infrared models show almost no isotropic component. The existence of an isotropic component for zodiacal dust orbits is questioned by comparison with the orbital elements of meteoroidal particles which serve as a source for the zodiacal dust by mutual collisions.

0. Introduction

It was shown (Giese and Kneiβel, 1987) that the three-dimensional distribution of dust may be represented by a lot of different latitude dependent density functions \( f(\theta) \). Recently dynamical analysis has revealed that models like the multilobe-model (Buitrago et al., 1983) demand for an unreasonable distribution of the inclinations (Kneiβel and Giese, 1986). Now again dynamical analysis of the 3D-density distribution has been involved.

1. Method and General Result

On account of the global rotational symmetry of the zodiacal dust cloud the arguments of perihelion and of the nodes of the zodiacal dust orbits are distributed randomly. According to Opik (Opik, 1951) this should be due to secular changes in the orbital elements from planetary perturbations. Not only lately this has been questioned for the small scale structures of the zodiacal dust cloud (cf. Gustafson, 1985).

Assuming further that the distribution of the semimajor axis and eccentricity may be separated from that for the inclinations (cf. Bandermann, 1968; Kessler, 1981) the relationship between the latitudinal dependent part of the density \( f(\theta) \) and the distribution of inclinations \( N(i) \) is given by Haug (Haug, 1958)

\[
f(B_0) = \frac{N(i)}{(\cos^2 B_0 - \cos^2 i)^2} \frac{d i}{172} \]

Thus the distribution of inclinations \( N(i) \) is to be determined as a solution from a Volterra integral equation of the first kind. As the density is the same for prograde and retrograde orbits of the same inclination the method is not capable in discriminating both types of orbits from one another \( N(i) e(0, r/2) \).

According to Dumont and Levasseur-Regourd (Dumont and Levasseur-Regourd, 1985) the scattering cross-section of the unit-volume and thus the density function \( f(B_0) \) should be smooth, which is true in almost all cases. Furthermore, the functions \( f(B_0) \) are monotonous falling ones in nearly all cases. Then the solution of \( N(i) \) consists of a sum in which one term is \( N sini \) and the other one is zero at the edges of the interval and gains a maximum inside (cf. Sneddon, 1966).

As the first term is known in orbital statistics (Bandermann, 1968) as an isotropic distribution it might be treated as a superposition of an isotropic part and, as we will soon see, a part whose most probable inclination is close to the ecliptic plane \( (i_{\text{max}} < 15^\circ) \).

If this interpretation is true, then the isotropic part should be extended to retrograde orbits. Thus from conservation of the numbers of orbits we have:

\[
N_0/2 \sin i, \quad 0^\circ \leq i < 180^\circ
\]

2. Distributions of Inclinations in Detail


According to the flatness of the isodensity lines the ellipsoid-model possesses a most probable inclination \( i_{\text{max}} \approx 10^\circ \), whereas the fan-model has one of \( i_{\text{max}} \approx 15^\circ \). Both models show an isotropic component being a little less or more than 10% of the whole number of orbits, demanding then for 5% of the orbits in retrograde direction.

Sombrero-model (Rittich, 1986, original concept by Dumont, 1976 at the XVI IAU General Assembly (Grenoble))

In this case the most probable inclination \( i_{\text{max}} \approx 10^\circ \). But, as one would expect from the bulge, \( \approx 20\% \) of the orbits should be spent in the isotropic component (That means, a fraction of 10% of the orbits is retrograde.).

Flattened fan-model (Deul and Wolsentnog, 1987)

In comparison to a classical fan-model \( i_{\text{max}} \approx 15^\circ \) and the isotropic component amounts \( < 8\% \).
Pole whole models (models by Lamy and Perrin, 1986; Good et al., 1986; Murdock and Price, 1985)
Pole whole models again have a most probable inclination of \( \approx 10° \), but there is only a negligible or no isotropic component (\(< 3\%\)).

Retrograde orbits amongst zodiacal dust particles

If we do not want to stay with a sharp unreasonable drop-off of the inclinations at 90° we have to take retrograde orbits into account.

Neither micro-meteoroid impact experiments (Grun et al., 1980; Grün and Zook, 1980; McDonnell, 1978) nor detection of the Doppler Shifts in Fraunhofer Lines (East and Reay, 1984; Fried, 1977; Hicks et al., 1974; James and Smeethe, 1970; Reay and Ring, 1968) report about retrograde orbits among the zodiacal dust cloud. There is one indication for an isotropic distribution of dust particles in the outer solar system (beyond Earth's orbit) by the PIONEER 10 and 11 experiments (Humes, 1980). But this is still in contradiction with the results from other experiments (Schuereman et al., 1977).

3. Suggestions Derived from the Orbital Elements of the Meteoroid Particle Cloud

To get some more insight into the problem it is useful to look at the inclination distribution of meteoroid particles which serve as sources by mutual collisions (Grü et al., 1985).

Comparison with the meteoroid distribution in inclination

Andreev and Belkovich (Andreev and Belkovich, 1985) prepared an inclination distribution of meteoroids \( (m \geq 10^{-7}g) \). This distribution has a most probable inclination at 22° and a relative strong isotropic component. So the distribution of meteoroidal orbits bears more orbits in high inclination than most of the zodiacal distributions. We want to give some tentative remarks explaining this disagreement between both clouds.

C2-meteoroids cannot give any input to the zodiacal cloud

According to Ceplecha (Ceplecha, 1977) the isotropic component called C2-meteoroids amongst meteoroidal particles \( (m \geq 10^{-7}g) \) belongs to orbits with very long semimajor axis and an eccentricity \( e \approx 0.99 \). They should amount about 30% of the whole distribution.

According to Jessberger (Jessberger, 1981) the particles have a density \( \rho = 0.65 \text{ g/cm}^3 \) and are classified as regular cometary material (So they should have a dark surface (cf. Giese et al., 1986)). As already pointed out the meteoroidal particles go into the zodiacal cloud as debris from mutual collisions. Particles bigger than a certain minimal size can stay in the solar system. Smaller particles are swept out by radiation pressure. Because the density of the dust cloud and the encounter velocity increases towards the Sun most of the collisions should take place in the perihelion of the particles (Bohnhany, 1978). In the perihelion the condition for an elliptic or bound orbit is immediately dependent on the eccentricity of the particles (Harwit, 1963). But the particles with \( e \approx 0.99 \) in the zodiacal size spectrum (10 \( \mu \text{m} \)- 100 \( \mu \text{m} \)) and \( \rho \approx 1 \) cannot stay in the solar system \( (\rho = 1 \text{ for black particles}, \rho \leq 1 \text{ g/cm}^3) \). This result seems to favour pole-whole models with almost no isotropic component. But we have to be careful, because there is a certain number of meteor streams with high inclination but small eccentricity \( e < 0.99 \). (The famous Orionids \( e = 0.962, i = 163.9° \) (Cook, 1973) and the \( \eta \)-Aurorids \( e = 0.958, i = 163.5° \) (Cook, 1973) associated with Comet P/Halley (Kresak, 1980)). Of course Sombrero-models and less the fan- or the ellipsoid-model have become questionable but the facts quoted are by far not sufficient to exclude these models.

References


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P. Babadzhanov: Distributions of meteors and Zodiacal Cloud are different. Do you think, that the Zodiacal dust cloud and meteoroids have different sources?

B. Kneissel: According to the results presented here meteoroid dust has a component, which could originate in long period comets. This component can't be a part of the zodiacal dust population as just explained. So it seems that zodiacal dust needs sources with mean inclinations $30^\circ$. This doesn't coincide with the inclination distribution of asteroids and short period comets.

H. Fechtig: Should you perhaps include dust particles from long period comets?

B. Kneissel: If one defines the long period comets as having a period $P > 2000$ then these comets have an eccentricity $0.97 < e < 1$ and an isotropic distribution of orbits over the sky. The input of larger particles by these comets into the solar system should be included in the meteoroid distribution given by Andreev and Belkovich (1985). Then the debris in the size range of zodiacal particles originating from these larger particles will be blown off the solar system by radiation pressure.

R. Dumont: It seems noteworthy that most of the curves, both for visible and for infrared data, nearly cross each other at about $15^\circ$ inclination. This could be more than fortuitous, and could mean (like in the method of the "nodes of lesser uncertainty") that the knowledge of the number of particles whose orbits are tilted by $\sim 15^\circ$ is less model-dependent than others.
Comets and asteroids are thought to be the main sources of interplanetary dust particles (IDPs). IDPs with a diameter < 50 μm are able to survive the entry into the Earth's atmosphere, where they can be collected without destruction. Because of their small size and mass, typically <10 μm and <10^{-9} g, their chemical analysis is difficult.

We introduce the proton microprobe for the non-destructive detection of trace elements in IDPs. Using the Heidelberg proton microprobe which provides a beam spot of < 2x3 μm², four IDPs have been analyzed and up to 26 elements were detected. To quantitatively evaluate the proton-induced X-ray spectra we calculated ab initio X-ray yields for the samples. Most elemental abundance ratios in three IDPs agree within a factor of two with those of cosmic abundance but with the notable exception of some volatile elements (P, Cu, Ga, Br, and Zn) which are strongly enriched. This is contrasting one IDP in which Ca and the volatile elements K, Zn and S are depleted.

Introduction

Comets are supposed to be the most pristine bodies in the solar system and their detailed in-situ exploration would greatly enhance the knowledge on early solar system processes. But because of their small size and high relative velocity access to comets is extremely difficult and expensive. On the other hand, comets, and asteroids, are thought to be the main sources of the interplanetary dust [1,2] and such interplanetary dust particles (IDPs) with diameters < 50 μm are able to survive the heating during entry into the Earth's atmosphere [3,4]. Thus IDPs from atmospheric collections probably are relatively unaltered material from comets and asteroids available to the analyst.

Because of the small size of the IDPs, typically in the 1-50 μm range, microanalytical methods are necessary for their investigation. The application of established sensitive techniques for chemical analysis, like ion microprobe and neutron activation, destroys or alters the samples [5]. The electron microprobe, which is limited in sensitivity mainly because of background by bremsstrahlung, provides information only on main and some minor elements. Since the proton mass is much larger than the electron mass, the background of bremsstrahlung by protons is much less. Thus proton induced X-ray emission spectroscopy (PIXES) allows the non-destructive determination of main, minor and trace elements in very small samples [6]. This is a report on our attempt to introduce the proton-microprobe for the bulk chemical analyses of IDPs.

Experimental

Two IDPs, Zodiac and Bounce (#13-06-05A and #14-03-09A, respectively), had been prepared by P. Fraundorf for examination with different electron microscopes [7]. They had been compressed to a thickness of 0.5 μm, floated on a thin carbon foil held by Cu and Au (Zodiac and Bounce, respectively) electron microscope grids, and coated with 15 nm carbon. The typical size of the fragments of the IDPs is 1 to 5 μm. For the used 3 MeV and 4 MeV protons the compressed IDPs are thin samples (area density < 0.15 mg/cm²), which implies that deceleration of protons and absorption of X-rays produced in the samples can be neglected.

Two other IDPs, SP85 and SP87 (#U2-22B14 and #U2-22B25, respectively), were made available and were prepared for analysis by D. Brownlee. These particles with a diameters of about 10 μm are mounted intact on carbon foils (~ 20 nm thickness) held by beryllium grids. In the case of these samples deceleration of protons and X-ray absorption, especially from low-Z elements, cannot be neglected and matrix corrections are necessary (see below).

The beam of the Heidelberg proton microprobe [8] can be focussed to a minimum size of 2x3 μm². Because of the low current density of the proton beam (~10 pA/μm²) and the mounting conditions of the IDPs, no excessive heating of the samples occurs. The excited X-rays are recorded with an energy-dispersive Si(Li) detector. Beryllium or aluminium absorbers with different thicknesses can be placed in front of the
detector to stop back-scattered protons and to avoid pile-up from low energy X-rays. The X-ray spectra were deconvoluted and the characteristic line intensities were evaluated with the SESAMX computer routine [9].

\[ R(z) = \omega z k_z e_z \sum_{i=1}^{n} \sigma_i(p_i) T_i(x_i) d x \]

Equation (1) can then be simplified to

\[ N_z = \frac{A_z n_z R_z \Delta \phi}{4\pi} \]

where \( N_z \) is the measured X-ray intensity. To eliminate the apparatus factors \( n_z \) and \( \Delta \phi \), which are difficult to measure, and because it is not necessary to obtain absolute atom concentrations, we normalize equation (3) to a reference element. The abundance ratio of element \( z \) over the reference element then is given by

\[ \frac{A_z}{A_{\text{ref}}} = \frac{N_z R_z}{N_{\text{ref}} R_{\text{ref}}} \]

For normalization we choose iron and not silicon because the X-ray quanta for silicon are absorbed by the 200 \( \mu m \) aluminium window. The applicability and reliability of this evaluation method has successfully been tested with two well-known, complex and thick standard materials [12].

Results and discussion

The PIXE spectra of the four IDPs were evaluated with SESAMX to obtain the net intensities of the main characteristic emission lines. With the X-ray yields calculated for these samples (Eqn. (2)) elemental ratios were then determined with Eqn. (4). The results are listed in Table 1 where upper limits are given if the error exceeds 50%. The cosmic abundances [13] of the elements detected by PIXE are also tabulated for comparison normalized to Fe.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>Mg/Fe</th>
<th>Zn/Fe</th>
<th>Zn/Fe</th>
<th>Zn/Fe</th>
<th>Fe/Sc</th>
<th>Fe/Co</th>
<th>Fe/Ca</th>
<th>Fe/Cr</th>
<th>Fe/V</th>
<th>Fe/Mn</th>
<th>Fe/Ni</th>
<th>Fe/Co</th>
<th>Fe/Co</th>
<th>Fe/Co</th>
<th>Fe/Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>2.2 \times 10^{-2}</td>
<td>1.1 \times 10^{-4}</td>
<td>1.4 \times 10^{-4}</td>
<td>1.6 \times 10^{-4}</td>
<td>1.8 \times 10^{-4}</td>
<td>1.5 \times 10^{-4}</td>
<td>1.5 \times 10^{-4}</td>
<td>1.8 \times 10^{-4}</td>
<td>1.6 \times 10^{-4}</td>
<td>1.2 \times 10^{-4}</td>
<td>1.0 \times 10^{-4}</td>
<td>1.2 \times 10^{-4}</td>
<td>1.0 \times 10^{-4}</td>
<td>1.2 \times 10^{-4}</td>
<td>1.0 \times 10^{-4}</td>
</tr>
</tbody>
</table>

Table 1: Summary of atom-ratios in interplanetary dust particles obtained by proton-induced X-ray emission spectrometry (PIXES). Cosmic abundances [13] are listed for comparison.

---

**Figure 1:** PIXE spectrum of the interplanetary dust particle SP87. (+) Experimental counts per channel; (---) main characteristic X-ray lines; (----) minor lines. Experimental conditions: 200 \( \mu m \) Al absorber, 4 MeV protons. Fe-esc.: artificial line from the Si(Li) detector.
At the first glance on Table 1 one notices that quite fewer elements - especially heavier ones - have been detected in Bounce and Zodiac than in SP85 and SP87. This is due to the superposition of the heavy element characteristic X-rays from the samples by those from the Au and Cu mounting grids excited by stray protons. After this experience IDPs SP85 and SP87 were mounted on Be grids. With this modification, 26 elements were detected and the abundances of some 16 elements were quantitatively determined in the latter samples. One also notices that the errors quoted for major elements like Mg, Si, and S are about as large as those for minor and rare elements. This is due to the fact that in this study the lower-energy X-rays were suppressed by the Al-absorber since we were most interested in the analysis of minor and higher-z elements. Over all the errors appear to be rather large (on the order of 20%). But they can be reduced by a factor of 2 when the integration time is prolonged by a factor of 3 which seems to be practicable.

Figure 2 shows the PIXE results on Zodiac and Bounce normalized to the cosmic abundance of the respective elements and also the results from an earlier SEM-EDX study of the same particles (7). Where comparison is possible the agreement is excellent. It is immediately obvious that with PIXE many more elements are quantitatively determined than with electron excitation. Zodiac overall is chondritic with notable enrichments of P and S. Bounce, on the other hand, is depleted in a number of elements like Ca, K, Zn and S.

Figure 3: Atomic abundances of the elements in the interplanetary dust particles SP85 (top) and SP87 (bottom) normalized to iron and their cosmic abundance. Upper limits are marked with arrows. The elements are arranged according to decreasing condensation temperature [14].

The normalized abundance patterns of the elements in SP85 and SP87 are shown in Figure 3. They are rather similar to each other in that most of the elements are present in chondritic proportion (within a factor 2) and in that some volatile elements are enriched relative to Cl. These are P, Cu, Ga, Br, and Zn. Anz et al. (16) by SXFPA analyses of the very same particles found comparable overabundances of these elements. Other IDPs also exhibit enrichments of volatile elements (17,18) which have been interpreted (17) as indicators of large scale elemental fractionation of the early solar system - which seems to be a bit over-shooting. We think that before such a far reaching conclusion can be defended more trivial reasons for the enrichments, e.g. contamination in the atmosphere or in the laboratory, have to be explored experimentally. Until that has been accomplished we refrain from the detailed interpretation of the results obtained from only that few particles.

The present study has shown that PIXE is a valuable non-destructive high sensitivity method for the chemical multi-element analysis of micro-samples. It easily can be combined with similar methods like SXFPA (16) and the less sensitive, but very accurate and well established SEM/TEM-EDX. It is essential that all this can be done prior to destructive studies with e.g. SIMS. Especially in combination with SXFPA trace element abundances in micro-grains can be obtained routinely with a high degree of confidence. We will fur-

![Figure 2](image2.png)

![Figure 3](image3.png)
cher explore this promising tool by increasing the proton beam luminosity and decreasing its diameter, by installing higher resolution detectors and integrating longer.

Acknowledgements

We are obliged to E. Zinner for providing us with Bounce and Zodiac and D. Brownlee for expertly mounting SP85 and SP87. We thank E. Bombelka for his advice with the spectra deconvolution, H. Blank and A. Janicke for help with microscopes and microprobes, O. Kress for drawing, and D. Krull for typing.

References:

[16] Ch. Antz, M. Bavdaz, E.K. Jessberger, A. Knöchel, and R. Wallenwein, these proceedings

Discussion

Shulman: Do you claim that your particles have avoided the heating crossing the upper atmosphere as well as all the standard meteoroid particles?
Wallenwein: I only underlined that there is no depletion of volatiles.
Shulman: But the volatiles are not free, they are strongly bound to the other atoms.
Wallenwein: I agree.
Lepiecha: Micrometer particles are decelerated high in the atmosphere without any significant heating. I want to encourage the authors in continuing this highly sophisticated and fine measurements. Their results could help to decide, if Brownlee’s particles are really of cometary origin.
CHEMICAL ANALYSIS OF INTERPLANETARY DUST PARTICLES WITH SYNCHROTRON RADIATION

Ch. Antz¹, M. Bavdaz², E.K. Jessberger¹, A. Knöchel², R. Wallenwein¹

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²Universität Hamburg, Institut für Anorganische und Angewandte Chemie, Martin-Luther-King-Platz 6, 2000 Hamburg 13, F.R.G.

Abstract:

Two 10-µm interplanetary dust particles collected in the stratosphere, have been analyzed with X-ray fluorescence excited by white synchrotron radiation (SYXFA) at the HASYLAB (DESY) in Hamburg. The measured abundances of the minor and trace elements with 16 < Z < 76 are in good agreement with abundances determined by PIXE analysis [1] of the same particles.

The results demonstrate that SYXFA is indeed a powerful non-destructive technique for multi-element analysis of micron-sized samples. Moreover we find that the combined application of two such techniques, SYXFA and PIXE, to the same valuable particle lends high credibility to the results.

Introduction: Two interplanetary dust particles (=IDPs) SP85 and SP87 [1] have been analyzed with white synchrotron radiation from the DORIS storage ring at DESY in Hamburg. The aim of this work was to test the applicability of Synchrotron X-Ray Fluorescence Analysis (=SYXFA) as a non-destructive method for the chemical multielement analysis of micro-samples, and to combine two different microanalytical techniques, PIXE [1] and SYXFA, on the same particles.

Theoretical calculations on proton (PIXE) and photon (SYXFA) interaction with matter, which take into account the differences of excitation processes, photo- and scatter-cross-sections for proton- and photon excitation yield: For the elements 15 < Z < 50 primary photons excite about 700 times more K\textsubscript{o} transitions and for the elements 40 < Z < 92 about 10-350 times more L\textsubscript{o} transitions than the same number of primary protons does [2]. The number of ionizations per unit deposited energy in a thin sample (e.g. 1 µm) is by a factor of 50 to 5000 larger for photon excitation than for proton excitation [3]. In the case of continuous photon excitation the signal/background ratios (=S/B) for both, PIXE and SYXFA, should be comparable, especially for elements with a Z > 30 [4]. With monochromatic photon excitation, the S/B ratio should increase by a factor of ~10 [5].

For the special case of multielement analysis of micro-samples conventional x-ray tubes would not be applicable because their photon fluxes and degree of polarization (~0.3-0.5) are too low. Synchrotron radiation (=S.R.), however, appears to be suitable for chemical microanalysis because it's unique properties like high brightness (Fig. 1), high degree of polarization (~0.9 for DORIS storage ring), and natural collimation (emission angle in GeV-energy region is about 0.1 m rad).

Fig. 1: In the energy region of interest the brightness of Synchrotron Radiation from DORIS is about three orders of magnitudes above the Cu-K\textsubscript{o} characteristic radiation from a 60 kw X-ray tube.
Two processes dominate when a photon interacts with an atom of the sample: a) The photoelectric effect produces an isotropic radiation pattern and yields the characteristic x-ray peaks of the elements. b) Scatter processes, such as coherent Rayleigh- and incoherent Compton-scattering, are mostly responsible for the background of the spectrum.

The differential cross-section for the scatter-process between a relativistic free electron and a plane polarized photon beam is [6,7]

\[
\frac{d\sigma}{d\Omega} = \frac{r_0^2}{\alpha} \left( \frac{\nu'}{\nu_0} \right) \left( \frac{\nu}{\nu'} \right)^2 \left( \frac{\nu'_0}{\nu_0} \right)^2 \left( 2 + 4\cos^2 \theta \right)
\]

with \(r_0\), the classical electron radius, \(\nu_0(\nu')\) the frequency of the incident (outgoing) photons, and \(\theta\) the angle between the electric polarization vector of the incident and outgoing photon. By choosing a plane of observation parallel to the plane of the storage ring and taking into account the definition for the polarization \(P = (I_x - I_y)/(|I_x + I_y|)\) with \(I_x, y\) - the intensities of incident beam in \(x, y\)-direction, one can calculate the amount of scattered intensity per unit solid angle in the direction of \(\Phi\) normalized to \(r_0^2\) and the incident intensity (\(\Theta\): scattering angle - angle of view):

\[
I = \frac{1}{2} \left\{ \begin{array}{c} \left( \frac{\nu}{\nu_0} \right)^2 \left( \frac{\nu'}{\nu_0} \right)^2 \left( \frac{\nu'_0}{\nu_0} \right)^2 \left( 2 + 4\cos^2 \Theta \right) \\
- (P+1) \sin \Phi \end{array} \right\}
\]

The intensity \(I\) is minimal when \(\Phi = 90^\circ\). Our experiment was performed with \(\Phi = 70^\circ\) because of sample mounting conditions, but in the future \(\Phi = 90^\circ\) can be used and thus the scattered intensities will be reduced by a factor of \(\approx 3\) (Fig.2).

Experimental: Fig.3 shows a schematic of the experimental setup used for SYXFA at the HASYLAB (DESY) in Hamburg. The S.R. from the DORIS storage ring passed a Mo-slit aperture, which defined a beam/specimen interaction area of \(\approx 10 \times 10 \mu m^2\), before hitting the target. The characteristic and background X-rays were sampled with a Si(Li) detector and analyzed by a Multi-Channel-Analyzer. The data were stored on a floppy-disk and mainly evaluated using the fit procedure XSPEK [13]. In order to preserve the natural collimation and intensity the primary beam passes through a tube with He-atmosphere up to near the Mo-slit. The whole experiment is placed in a small lead chamber to prevent health hazards due to high energy X-rays.

Results: Fig.4 shows the SYXFA spectra of SP85 and SP87 and for comparison a PIXE-spectrum of SP87 [1]. Full vertical lines in the spectra represent the most intensive peaks of the elements; dotted lines are used for secondary peaks. Kr and Ar in the SYXFA spectra are signals from air in the lead chamber. Detection of As-K and Os-L signals are difficult because both overlay with the Pb-L-peak from lead background radiation of the chamber.

![Fig. 3: Schematic for the experiment.](image)

![Fig. 2: Relative scatter intensity as a function of scattering angle \(\Phi\). In our experiment \(\Phi = 70^\circ\) whereas the lowest scattering background achievable is at \(\Phi = 90^\circ\).](image)
In Table 1 the atom-ratios obtained by SYXFA are listed normalized to Fe and compared to the respective cosmic abundances. In Fig. 5 the atom-ratios, normalized to cosmic abundances, are plotted. The elements are arranged according to their volatility [14]. For the elements with a fitted relative error greater than 50% (V, Se) or those overlapping with others (As-Os-Pb, Ti-Fe-escape, Cu-Fe) we calculated upper limits, represented in Fig. 5 by arrows. For both particles the abundance patterns of the more refractory elements are almost cosmic, whereas the more volatile elements are enriched relative to their cosmic abundances.

In Table 1 the atom-ratios obtained by SYXFA are listed normalized to Fe and compared to the respective cosmic abundances. In Fig. 5 the atom-ratios, normalized to cosmic abundances, are plotted. The elements are arranged according to their volatility [14]. For the elements with a fitted relative error greater than 50% (V, Se) or those overlapping with others (As-Os-Pb, Ti-Fe-escape, Cu-Fe) we calculated upper limits, represented in Fig. 5 by arrows. For both particles the abundance patterns of the more refractory elements are almost cosmic, whereas the more volatile elements are enriched relative to their cosmic abundances.

**Fig. 4:** Spectra of SP85 (a) and SP87 (b) excited with white S.R. Sampling time ~ 430 min. Full lines represent main characteristic X-ray signals, dotted lines minor signals.

**Fig. 5:** Atom-ratios obtained by SYXFA normalized to Fe and cosmic abundances. The elements are arranged according to their volatility. Upper limits are represented by arrows.

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**TABLE 1:** Atom-ratios in the IDPs SP85 and SP87 obtained with SYXFA. Cosmic ratios are listed for comparison.

<table>
<thead>
<tr>
<th>Atom-ratio</th>
<th>SP85</th>
<th>SP87</th>
<th>Cosmic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu/Fe</td>
<td>&lt;6.95·10^{-3}</td>
<td>9.78·10^{-3}</td>
<td>5.40·10^{-3}</td>
</tr>
<tr>
<td>Mn/Fe</td>
<td>&lt;3.00·10^{-4}</td>
<td>2.96·10^{-4}</td>
<td>2.95·10^{-4}</td>
</tr>
<tr>
<td>Ti/Fe</td>
<td>8.72·10^{-3}</td>
<td>&lt;5.80·10^{-3}</td>
<td>5.80·10^{-3}</td>
</tr>
<tr>
<td>V/Fe</td>
<td>2.57·10^{-2}</td>
<td>&lt;6.87·10^{-2}</td>
<td>6.87·10^{-2}</td>
</tr>
<tr>
<td>Co/Fe</td>
<td>&lt;2.37·10^{-4}</td>
<td>&lt;7.32·10^{-5}</td>
<td>&lt;7.32·10^{-5}</td>
</tr>
<tr>
<td>Cr/Fe</td>
<td>&gt;6.23·10^{-3}</td>
<td>&gt;1.61·10^{-2}</td>
<td>&gt;1.61·10^{-2}</td>
</tr>
<tr>
<td>Ni/Fe</td>
<td>1.86·10^{-2}</td>
<td>&lt;1.33·10^{-2}</td>
<td>&lt;1.33·10^{-2}</td>
</tr>
<tr>
<td>Cu/Fe</td>
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<td>&lt;1.32·10^{-4}</td>
<td>&lt;1.32·10^{-4}</td>
</tr>
<tr>
<td>As/Fe</td>
<td>&lt;9.60·10^{-5}</td>
<td>&lt;7.56·10^{-5}</td>
<td>&lt;7.56·10^{-5}</td>
</tr>
<tr>
<td>Mn/Fe</td>
<td>&lt;4.05·10^{-3}</td>
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<td>&lt;7.32·10^{-4}</td>
</tr>
<tr>
<td>Fe/Fe</td>
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<td>&gt;1.06·10^{-2}</td>
<td>&gt;1.06·10^{-2}</td>
</tr>
<tr>
<td>Zn/Fe</td>
<td>&lt;3.10·10^{-3}</td>
<td>&lt;1.84·10^{-3}</td>
<td>&lt;1.84·10^{-3}</td>
</tr>
<tr>
<td>Sc/Fe</td>
<td>&lt;2.96·10^{-3}</td>
<td>&lt;1.84·10^{-3}</td>
<td>&lt;1.84·10^{-3}</td>
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<tr>
<td>Ca/Fe</td>
<td>&lt;5.61·10^{-2}</td>
<td>&lt;3.89·10^{-2}</td>
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<td>Br/Fe</td>
<td>&lt;1.24·10^{-2}</td>
<td>&lt;1.06·10^{-2}</td>
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</tr>
<tr>
<td>K/Fe</td>
<td>&lt;3.30·10^{-3}</td>
<td>&lt;1.84·10^{-3}</td>
<td>&lt;1.84·10^{-3}</td>
</tr>
<tr>
<td>Br/Fe</td>
<td>&lt;1.06·10^{-2}</td>
<td>&lt;1.06·10^{-2}</td>
<td>&lt;1.06·10^{-2}</td>
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<td>Rb/Fe</td>
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<td>S/Fe</td>
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<td>&lt;1.84·10^{-3}</td>
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<td>Sc/Fe</td>
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<td>&lt;1.61·10^{-2}</td>
<td>&lt;1.61·10^{-2}</td>
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<tr>
<td>Os/Fe</td>
<td>&lt;6.23·10^{-3}</td>
<td>&lt;1.61·10^{-2}</td>
<td>&lt;1.61·10^{-2}</td>
</tr>
</tbody>
</table>
The spectrum sampling time for PIXE was generally five times longer than for SYXFA. A comparison of the spectra obtained with both methods shows that:

- SYXFA has a higher integral count rate and thus a better count statistic than PIXE (even in 1/5 of time).
- SYXFA has a better signal/noise-ratio for the elements with Z > 30 and is comparable for the other elements.
- S/B of SYXFA is comparable to that of PIXE. It decreases however for elements with 15 < Z < 30 due to the continuous photon excitation.

A comparison of the results for SP85 and SP87 obtained by PIXE and SYXFA shows that both reproduce nearly the cosmic abundance patterns of the more refractory elements as well as the enrichment of the volatiles like Ga, Ge, Br, Se, Zn, and S.

Possible interpretations: Possible interpretations of the observed elemental patterns of the particles include:

- IDPs may originate from even less metamorphosed parent bodies than CI-Meteorites are [9,10]. Cometary dust grains show an enrichment of light volatiles like C and N relative to CI [11]. Thus the overabundance of the minor volatile elements in the IDPs may indicate a relation of IDPs and comets.
- Contamination could occur during the entry of the particles into the Earth’s atmosphere and also during laboratory processing, both, however, regarded to be very unlikely but cannot be excluded.

Conclusions: The pilot experiment with SYXFA shows that this novel technique is a powerful tool for multi-element microanalysis of micro-samples, e.g., it was possible to detect in SP87 an amount of ~10^-14 g Se (~8·10^9 atoms) without destroying the sample. For the future it is planned to increase the spatial resolution to ~1 μm, using a coded irradiation technique, to allow a space-resolved analysis of micro samples [12]. Secondly the scattered intensity will be reduced by a factor of about 3 by choosing a view angle of 6–90°.

References
[1] B. Wallenwein, Ch. Antz, E.K. Jessberger, K. Traxel. see these proceedings

DISCUSSION

Henning: Can you make any comments on the mineralogical structure of IDP's with your new techniques?

Antz: We can only determine the average elemental ratio within: certain error limit.

Ceplecha: I see no with my remark to the Wallenwein et al. paper.

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Cometary dust grains as measured by the Halley space missions show a silicate- and a light element component. The latter most likely represents an organic material. The densities of the grains are mostly below 1 g/cm$^3$. The organic component slowly decays at higher temperatures during subsequent perihelion passages. Therefore the "older" cometary grains are different from the "young" cometary grains: they show higher albedos, higher densities and orbit finally within the inner solar system.

The dust impact analyzer experiments on Giotto and Vega have shown that cometary dust generally consists of two components: a silicate component and a light element component (Krueger and Kissel, 1987). This result is compatible with the model for dust grains suggested by Greenberg (Greenberg, 1982). Therefore, dust grains may have fluffy structures consisting of submicron-sized building blocks of silicate cores and organic mantles. The dust impact analyzer has directly measured the densities of cometary dust grains ranging between 0.1 and 3 g/cm$^3$.

Before discussing the evolution of cometary dust grains, some observations for the interplanetary dust are summarized:

(a) Lunar microcraters: it was possible to directly measure the density of interplanetary grains by studying the morphology of lunar microcraters (Brownlee et al., 1974; Smith et al., 1974; Nagel et al., 1975; Nagel et al., 1976). Simulation experiments have shown that the diameter to depth ratios of microcraters are directly correlated with the densities of the projectiles (Vedder and Mandeville, 1974; Nagel and Fechtig, 1980; Fechtig, 1982). An analysis has shown that less than 30% of all lunar microcraters are produced by low density projectiles.

(b) Helios dust experiment: the analysis of the dust experiment from the Helios space mission has shown the existence of two different types of particles: dust grains of normal densities ($\rho = 3$ to 8 g/cm$^3$) on quasi-circular orbits around the sun ($e < 0.4$) and dust grains of low densities ($\rho < 1$ g/cm$^3$) on high eccentric orbits around the sun ($e > 0.4$) (Grun et al., 1980). But again less than 30% of all observed particles are in the second class with fluffy type structures.

(c) Pioneer 10/11 dust experiments: the two dust experiments have received observations which seem to contradict each other. The optical experiment (Hanner et al., 1976) has observed a particle number density dependency which roughly is in inverse proportion to the distance from the sun until 3.3 AU. Furthermore, no scattered sunlight has been recorded. The penetration experiment (Humes et al., 1974; Humes, 1980) however, has seen a similar dependence between 1 and 3.3 AU, but furtherout a constant dust flux has been recorded until 20 AU. Several authors (Cook, 1978; Fechtig, 1984) have tried to solve this contradiction by suggesting a continuous decrease of the albedos of dust particles proportional to the distance from the sun.

Can the cometary particles as measured during the Halley-missions explain all these observations?

An explanation would be easy if one assumes the asteroids as a second source for the interplanetary dust, a source at least as strong as the cometary source. If this was the case, then asteroidal dust of high albedos would populate the inner solar system between the sun and the asteroidal belt, and cometary particles of low albedos with considerable aphelion distances would stay only temporarily in the inner solar system. In this case, the inner solar system would be "dominated" by the high albedo asteroidal dust. This would fit to the observations obtained by lunar microcraters as well as by the Helios results and would explain the Pioneer 10/11 findings.

However, the asteroids are only a weak source for dust, as shown by the Pioneer 10/11 dust experiments (Humes et al., 1974; Kessler, 1970): the expected increase when travelling through the asteroidal belt did not occur. Also Dohnanyi (1976) has shown that the asteroids
do not produce enough dust to play a role in the inner solar system.

Therefore one should neglect an asteroidal source and only consider the main cometary source. Let's follow the possible fate of cometary dust from its release from the cometary nucleus:

--- cometary dust grains of the above mentioned properties and structures are released and either leave the solar system immediately through the dust tail of the comet (generally the case for submicron-sized dust grains) or they stay on the cometary orbit and form a meteoroid stream (generally the case for micron-sized and larger dust grains)

--- all grains of a meteor stream are periodically heated up during subsequent perihelia passages. Therefore the following question arises: Do the particles change their compositions and structures? It is well known that organic components can not survive at temperatures above a certain threshold. They generally decay at a few hundred degrees. In an earlier paper (Mukai and Fechtig, 1983), the assumption of a decay rate of approximately \(10^{-13} \text{ g/cm}^2 \text{ sec}\) for Halley dust grains lead to a slow variation in composition and structure. For individual grains, the organic component slowly decreases from the outside to the interior. After about \(10^4\) to \(10^5\) years, the organic material essentially has disapp-eared and only the stable silicates remain. As a result, the Brownlee-particles are evolved. Since silicates generally show higher albedos, these "old" cometary particles have higher albedos compared to the albedos of the "young" cometary grains (Mukai et al., 1986);

--- the Poynting-Robertson effect has changed the orbits of the cometary dust grains considerably during the time in discussion. After \(10^4\) to \(10^5\) years the orbits of cometary grains are much more circle-like and hence the particles orbit much longer and most of them always within the inner solar system.

Thus we can conclude that almost all dust particles in the solar system are of cometary origin. In the course of time there is a decrease of the organic component which causes an increase in the albedos. Old particles with high albedos, staying essentially in the inner solar system are mainly silicate grains.

References:


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DISCUSSION

Olsson-Steel: The lunar microcrater data indicating a minority of these to be due to low-density particles is concordant with the meteor data: our meteor density data is almost all from comet-related showers and hence the meteors are low-density; the only asteroid-related shower (the Geminids) renders a higher density. In addition, the absence of dust (or, at least, scattered light) at r > 3.3 AU is not in contradiction with the meteoroid distribution since what is important is where the meteoroids are disrupted to form dust: this occurs predominantly at small heliocentric distances, so that the source function for the dust is very different to the meteoroid distribution and much more like the zodiacal dust distribution.

Ceplecha: About 20% of the photographic meteors have atmospheric trajectories, which can be better explained by assuming heavy-coated particles rather than particles of homogeneous composition. This may be an additional support to the model you propose.

Giese: The polarization of scattered light, which decreases with decreasing solar distance (cf. Leinert et al., Dumont and Levasseur-Re- gourd) depends on both the absorption of the material and the structure of the particles. If fluffy particles become too compact, there might be problems, even if absorption decreases. Can you say something about the changes in structure?

Fechtig: I would expect that upon the continuous slow release of organic mantle material the silicate cores remain on from Brownlee particles. The albedos and the densities of Brownlee particles are higher than those of "young" cometary grains. The structure should be more compact, too.

Hajduk: The model of particles, used in this paper fully corresponds to the observed mass distribution of particles, requiring the fragmentation and evaporation of larger bodies during their returns to perihelion.
DYNAMICS OF INTERPLANETARY DUST

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The dominant forces determining the motion of interplanetary particulates are gravitation, solar radiation pressure and Lorentz force. The latter two becoming significant for micron- and submicron-sized particles. In situ measurements by spaceprobes, microrater distributions and remote observations both in the IR and visible wavelength range have established the mass frequency and spatial distribution of dust particles in interplanetary space. Consequences of the Poynting-Robertson effect and mutual collisions on these distributions and the contributions of various sources (interstellar dust, asteroids and comets) are discussed. It is shown that the contribution from a distributed source of large particles in the inner solar system is most important. Collisions between these meteor sized particles \((m > 10^{-5} \text{g})\) produce large amounts of zodiacal light particles \((10^{-10} \text{g} \text{ to } 10^{-5} \text{g})\) and \(\beta\)-meteoroids \((m < 10^{-10} \text{g})\) which leave the solar system on hyperbolic orbits. At the present time the Poynting-Robertson effect transports into the inner solar system less than 10% of the zodiacal light particles which are produced by collisions from bigger particles.

I. Introduction

Craters on the lunar surface proved that a continuous spectrum of interplanetary particulates exists from km-sized boulders (small asteroids and comets) to submicron sized dust grains. The dominant force for all particles, except for the smallest dust grains is the solar gravitational attraction

\[
F_{\text{grav}} = \frac{GM_{\odot} m}{r^2} = 2.5 \cdot 10^{-8} \rho \left( \frac{r}{r_{\odot}} \right)^{-2}
\]

where \(M_{\odot} = 1.99 \cdot 10^{33} \text{g}\) is the solar mass. With particle radius \(s\) in (cm), its density \(\rho\) in \((\text{g cm}^{-3})\) and \(r_{\odot} = 1 \text{ AU}\) the gravitational force is given in dynes. Scattering and absorption of solar radiation by an interplanetary particle leads to a radiation pressure force \(F_{\text{rad}}\) directed almost radially outward (cf. Burns et al., 1979). The ratio of radiation pressure to gravitational attraction (both forces have the same dependence with solar distance \(r\)) has for spherical particles the value (Dohnanyi, 1978)

\[
\beta = \frac{F_{\text{rad}}}{F_{\text{grav}}} = 5.7 \cdot 10^{-5} \frac{Q_{\text{pr}}}{\rho s}
\]

with \(Q_{\text{pr}}\) being an efficiency factor for the momentum transfer. \(Q_{\text{pr}} = 1\) for a perfectly absorbing sphere, for real particles, however, \(Q_{\text{pr}}\) decreases for decreasing \(s\) below \(10^{-4}\) cm (i.e. order of the effective wavelength of the solar light, Burns et al., 1979). Therefore \(\beta\) has its maximum value for absorbing particles (like carbon or magnetite) at \(\beta = 2\) to 5 and for dielectric particles (like silicates) at \(\beta = 0.5\) to 1. Radiation pressure may dominate in the size regime from \(10^{-5}\) to \(10^{-6}\) cm, below that it becomes less important again.

The photoelectric effect from the solar UV radiation is expected to develop a net positive charge \(Q\) (e.s.u) on interplanetary particles corresponding to a surface potential \(\phi\) of about +5 V

\[
Q = \frac{s \phi}{300} = 4.8 \cdot 10^{-10} N_e
\]

where \(N\) is the number of elementary charges \(e\) on the grain. Once charged, the interplanetary magnetic field will exert a force on these particles and hence influence their orbit. The Lorentz force \(F_L\) is given by

\[
F_L = \frac{Q}{c} (\mathbf{v} \times \mathbf{B})
\]

where \(\mathbf{v} = \mathbf{v}_{sw} + \mathbf{u}\). Here \(\mathbf{v}_{sw}\) is the solar wind speed \((400 \text{ km s}^{-1}\) in the radial direction) and \(\mathbf{u}\) is the orbital velocity of the particle (typically \(30 \text{ km/s}\)) and \(\mathbf{B}\) is the magnetic field strength (about \(5 \cdot 10^{-5} \text{g}\) at an angle of \(45^\circ\) with respect to the radial direction at \(1 \text{ AU}\)). With these values at \(1 \text{ AU}\) equ. (4) becomes

\[
F_L = 1.4 \cdot 10^{-10} \mathbf{s} \phi \ [\text{dynes}]
\]

Comparison of (5) with (1) shows \((\phi = 5V\) and \(\rho = 2.5 \text{g cm}^{-3}\)) that for \(s \leq 10^{-5}\) cm the Lorentz force becomes dominant.

Dynamics of small interplanetary particles including gravity and radiation pressure have been discussed by Robertson (1927); Wyatt and Whipple (1950); Briggs (1962); Whipple (1967), Singer and Bandermann (1967); Dohnanyi (1978). Electromagnetic effects on particles orbiting the sun have been included by Parker (1964); Morfill and Grün (1979a); Consolmagno (1979); Barge et al. (1982); Hassan and Wallis (1983). The dynamic effects on interstellar particles entering the solar system were treated by
Levy and Jokipii (1976) and Morfill and Grün (1979b). A review of the interaction of solid particles with the interplanetary medium can be found at Morfill et al. (1985).

II. Size Frequency and Spatial Distribution of Interplanetary Dust

Information on the distribution of interplanetary meteoroids is obtained from lunar crater statistics, in situ spacecraft measurements, meteor and zodiacal light observations. Grün et al. (1985) derive a flux model with the following characteristics (see Fig. 1):

Meteoroid observations (for a summary see Whipple, 1967) lead to a dependency of the cumulative flux on the meteoroid mass \( m \) according to \( m^{-1.3} \) for masses \( m < 10^{-14} \) g. The flux of smaller particles down to mass \( m < 10^{-10} \) g is characterized by the size distribution of lunar micrometeoroids (e.g., Morrison and Zinner, 1977). The absolute calibration of the fluxes at masses \( 10^{-7} \) g and \( 6 \times 10^{-7} \) g is obtained from measurements of the Pegasus satellite (Nauman, 1966). At \( m = 10^{-13} \) g and \( 10^{-12} \) g fluxes have been derived from the HEOS 2 experiment (Grün and Zook, 1980). These fluxes are below most lunar micrometeoroid fluxes because the latter are dominated by secondary ejecta cratering (Zook et al., 1984) for particle masses \( m < 10^{-10} \) g. In the mass range \( 10^{-14} \leq m \leq 10^{-9} \) g, the slope of the cumulative meteoroid flux is \( -0.36 \). The flux of smaller particles \( (m < 10^{-14} \) g) has been calculated from a collisional model assuming that all fragments of this size range which are produced inside 1 AU are pushed out of the solar system by radiation pressure and become \( \beta \)-meteoroids (Zook and Berg, 1975).

This interplanetary flux leads to a spatial mass density at 1 AU of \( \sim 10^{-14} \) g cm\(^{-3}\), where most mass per logarithmic mass interval is in meteoroids of masses \( 10^{-7} \) g to \( 10^{-6} \) g. Measurements of the zodiacal light (Leinert et al., 1981) provide the radial dependence of the spatial number density \( n \) of interplanetary meteoroids: \( n \sim r^{-1.3} \). The determination of the color of the zodiacal light (Pitz et al., 1979) shows a considerable reddening compared to the solar spectral flux. This observation is compatible with the characteristics of the flux curve, i.e., most cross-sectional area per logarithmic mass interval originates from particles of masses \( 10^{-8} \) g to \( 10^{-7} \) g. The total cross-sectional area of the interplanetary meteoroid cloud at 1 AU is \( 5 \times 10^{-19} \) m\(^2\) m\(^{-3}\).

III. Dynamical Effects on Submicron-Sized Particles

For submicron-sized particles the effect of solar attraction is strongly reduced by radiation pressure and the Lorentz force. Therefore these small particles move mostly on bound hyperbolic orbits. There are two types of particles which move on hyperbolic orbits inside the solar system: (1) Interstellar dust grains which traverse the inner parts of our solar system and (2) small particles which are generated from larger bodies either by collisions (\( \beta \)-meteoroids) or by emission from comets when they get close to the sun and sublimation of the icy bonding material takes place (generally inside 5 AU from the sun). The latter particles are brought from bound orbits of their parent bodies onto hyperbolic orbits by the additional significant action of radiation pressure.

The fluxes of these different particle populations on hyperbolic orbits show quite different characteristics. Interstellar dust grains in the vicinity of the solar system amount to \( 10^{-27} \) g cm\(^{-3}\) or \( 10^{-26} \) g cm\(^{-3}\). The higher value is derived from the average interstellar extinction of 1 mag per kpc (Greenberg, 1973) while the lower value assumes that the solar system is currently surrounded by low density warm interstellar material of density \( \sim 10^{-25} \) g cm\(^{-3}\), one percent of which is in dust (Wood et al., 1985). We will use this lower value in the following discussion. The sun moves with respect to this material at a speed of 20 km/s which amounts to a mass flux of \( 2 \times 10^{-17} \) g m\(^{-2}\) s\(^{-1}\). If we assume that most mass is in dust interstellar particles of \( s = 0.1 \mu \text{m} \) \( (m = 10^{-14} \) g) or \( s = 0.01 \mu \text{m} \) \( (m = 10^{-17} \) g) then a flux of \( 2 \times 10^{-3} \) or 2 particles m\(^{-2}\) s\(^{-1}\), respectively, is expected to arrive from the solar apex direction. This high flux has not been observed. There are several reasons to explain this deficit in the flux of interstellar particles. These small particles may have \( \beta \)-values in excess of 1 especially if they are made out of absorbing material. For example interstellar particles with \( \beta = 2 \) \( (s = 0.01 \mu \text{m graphite grains}) \) will reach just as close as the distance of Jupiter before radiation pressure deflects them out again. Volatile icy constituents will sublime inside 3 to
be largely excluded from the solar system by the magnetic field which extended to 15° ecliptic latitude. Model of the sector structure of the interplanetary plasma and magnetic field on 3-meteorids either to a "focusing" or "defocusing" of interstellar dust. More detailed study by Morfill and Grim (1979b) showed that submicron sized interstellar grains will sweep action of the solar wind magnetic field. A steady stream of particles on hyperbolic orbits originates from collisions of larger meteoroids in the inner solar system. Grün et al. (1985) estimated that this flux of β-meteoroids from the solar direction is $10^{-1}$ and $3 \cdot 10^{-4}$ particles m$^{-2}$ s$^{-1}$ for particles of $s > 0.01$ μm and $s < 0.01$ μm, respectively, and it corresponds to a mass flux of $3 \cdot 10^{-22}$ g m$^{-2}$ s$^{-1}$ at 1 AU in the ecliptic plane which has been observed by the dust experiments on board Pioneer 8 and 9 (Berg and Grün, 1973).

Levy and Jokipii (1976) studied the effects of the interplanetary magnetic field on charged interstellar grains penetrating the solar system. They suggested that submicron sized interstellar grains will be largely excluded from the solar system by the sweeping action of the solar wind magnetic field. A more detailed study by Morfill and Grün (1979b) showed that the unipolar field regimes at high latitudes lead to 20° equatorial plane (i.e. approx. within 20° ecliptic latitude). The stochastic magnetic fluctuations in the equatorial region caused by the warping of the current sheet which separates the polar field, leads to a diffusive transport of particles of sizes $s < 10^{-5}$ cm. They concluded that dust particles with radii $s > 10^{-5}$ cm can penetrate deeply into the heliosphere if their incidence direction at the heliopause is almost radially inward and close to the solar magnetic equatorial plane (i.e. approx. within 20° ecliptic latitude). Particle trajectories coming from high solar magnetic latitudes are focused towards the solar magnetic equatorial plane during solar cycles of negative field polarity in the northern hemisphere. During other solar cycles the inner heliosphere is shielded from interstellar grains approaching from high latitudes.

Numerical trajectory calculations have been performed using the code described by Morfill and Grün (1979a) in order to study the effects of the interplanetary plasma and magnetic field on β-meteoroids (Morfill et al., 1985). The basis was a realistic model of the sector structure of the interplanetary magnetic field which extended to 15° ecliptic latitude. As initial conditions it was assumed that particles were created on orbits with inclinations $i = 0°$ and $30°$ and with the local Keplerian velocity for circular orbits. Because of their radiation pressure values $\beta > 0.5$ these particles would leave the solar system on hyperbolic orbits just because of the radiation pressure alone.

**IV. Dynamics of zodiacal light particles**

Particles which contribute most to the zodiacal light brightness are 10 to 100 μm in radius. The orbital evolution of these particles is dominated by the Poynting-Robertson drag (Roberson, 1937; Wyatt and Whipple, 1950; Burns et al., 1979) which causes the particle to lose orbital angular momentum by the interaction with solar photons and solar wind ions. The life time due to radiation pressure drag of a particle to spiral form an initial orbit (with semi-major axis $a_0$ and eccentricity $e_0$) into the sun is

$$ t_{PR} = \frac{7 \cdot 10^6 \, s \cdot Q \cdot a_0^2 \cdot \eta(e_0)}{\pi} \text{[years]} \quad (6) $$

where $\eta(e_0)$ is a factor ($\eta(0) = 1$) which decreases with increasing $e_0$ (Wyatt and Whipple, 1950). Solar wind ion drag reduces these life times additionally by about 30%.

The inward mass flux of micron to mm-sized particles due to the Poynting-Robertson effect in the ecliptic plane at 1 AU is $2.1 \cdot 10^{-22}$ g cm$^{-2}$ s$^{-1}$ (Grün et al., 1985). Because of the increased spatial density towards the sun (Leinert et al., 1981) the inward flux at the inner edge of the zodiacal cloud will increase by a factor 2 to 3, depending on where the inner edge is assumed to be (0.1 AU or 0.03 AU) and where sublimation of meteoritic material occurs. The evaporated atoms (mostly C, O, Mg, Si, S, and Fe) will be ionized by photoionization and charge exchange reactions and will subsequently be convected along with the solar wind and the interplanetary magnetic field.

Outside 1 AU asteroidal debris will contribute to the interplanetary particulate cloud. Observations of the thermal radiation with the infrared satellite IRAS (Hauser et al., 1984) showed high intensities at wavelength of 12 to 100 μm in the ecliptic plane and in bands on both sides about 10° away from it. These observations have been interpreted by Dermott et al. (1984) as being due to impact ejecta particles from the known asteroids.

Measurements of the impact rate of interplanetary dust particles onto the Pioneer 10 spacecraft out to 20 AU has been reported by Humes (1980). He found that outside Jupiter’s orbit the particle flux stayed about constant. If this result is not just caused by bad statistics which is possible since the total number of impacts was only about 30 - then there is a problem with understanding this spatial distribution. The radial drift velocity due to the Poynting-Robertson effect is proportional to $1/r$ for circular orbits. Therefore inside the source region of interplanetary particles a spatial density variation $n(r) \sim r^{-\alpha}$ ($\alpha=1$) turns up. If the orbits are eccentric
or if there is a source for dust particles in that region of space then an even steeper radial dependence ($a > 1$) results (Leinert et al. 1983). Only if there is a sink for particles in the region of space under consideration then a flatter slope ($a < 1$) would be expected. Sublimation of water ice (Zook 1980) or sputtering and sublimation of volatile organic mantles (Fechtig 1987) have been proposed as loss mechanisms.

The plane of symmetry - interplanetary dust has been found to deviate slightly from the ecliptic plane. Inside 1 AU its ascending node and inclination were determined by Helios to be $\Omega = 87^\circ \pm 4^\circ$, $i = 3.0^\circ \pm 0.1^\circ$ (Leinert et al. 1980), a result with which the earthbound observations of Misconi and Weinberg (1978) fully agree. There is evidence that outside 1 AU the symmetry is closer to the orbit of Mars or the invariant plane of the solar system (Misconi 1980, Dumont and Levasseur-Regourd, 1987), which is also supported by the analysis of IRAS infrared measurements (Hauser et al., 1985).

V. Effects of mutual collision

In collisions between interplanetary meteoroids the impact speed usually is high enough to result in fragmentation of one or both particles. The average impact speed is generally approximated by

$$v(r) = v_0 \left( \frac{r}{r_0} \right)^{-0.5} \quad (7)$$

with $v_0 = 20$ km/s at $r_0 = 1$ AU. In such a collision the smaller particle always gets destroyed, the larger fragments only, if the mass ratio is not too large, i.e. if

$$m_{\text{projectile}} \geq \frac{1}{\Gamma(v)} m_{\text{target}}, \quad (8)$$

where $\Gamma(v) = 250 v^2$ (km/s) was found experimentally for basalt and may be typical for interplanetary particles also. If the projectile mass is smaller, the large particle is eroded by the impact crating process. Dohnanyi (1970) showed that for the meteoroids with masses $m < 10^{-1}$ g erosive collisions are much less important than catastrophic collisions, so that we limit our discussions to the latter case.

The rate of catastrophic collisions of a meteoroid of mass $m$ is given by adding the probabilities that the meteoroid will encounter a large enough projectile particle during the following second over all projectile masses $m_p$:

$$C(m,r) = \int_{m_p}^{M} \sigma \cdot n(m_p,r) \cdot v(r) \cdot \frac{d m_p}{\Gamma(v)} \quad (9)$$

The cross-section is $\sigma = a (s + s_p)^2$, where $s$ and $s_p$ are the particle and projectile radii respectively. The collisional lifetime for this particle then is

$$\tau_c(m,r) = \frac{1}{C(m,r)} \quad (10)$$

Fig. 2 shows the so calculated collisional lifetimes. At 1 AU the lifetimes are shortest ($10^6$ years) for particles of mass $10^{-3}$ g to $1$ g. Both bigger and smaller particles have longer collisional lifetimes. For comparison we also show the Poynting-Robertson lifetimes. The efficiency factor used was that for olivine particles and the average initial eccentricity of the particle orbits at 1 AU is assumed to be 0.5.

Collisions dominate the lifetimes of meteoroids with masses $m \geq 10^{-5}$ g. These large particles will not change their orbits significantly due to the Poynting-Robertson effect before they are involved in a collision and fragmented into smaller particles. Only smaller particles ($m < 10^{-5}$ g) will have their orbits circularized by the Poynting-Robertson drag and will eventually spiral in towards the sun where they will evaporate.

The mass of particles in the interval $(m_1, m_2)$ lost by catastrophic collisions per second is given by

$$M(m_1, m_2) = - \int_{m_1}^{m_2} n(m,r) \cdot C(m,r) \cdot dm \quad (11)$$

Dohnanyi (1969) showed that an interesting conclusion can be drawn from the above relations, assuming only conservation of mass. If the mass distribution $n(m)$ is steep, i.e. if there are many smaller projectiles, much mass will be lost from a given size interval. If the distribution is flat there are fewer projectiles which are able to fragment larger target particles. Balance between production and destruction is achieved for $n(m) \sim m^{-11/6}$, a mass distribution which was observed for the smaller asteroids (Dohnanyi 1969). A particle population with an index $\gamma > 11/6$ is decaying under the influence of catastrophic collisions and an extra source of particles is required to maintain their distribution. This is the case for meteoroids of mass $m \geq 10^{-5}$ g (Fig. 3). For a population index $\gamma < 11/6$ we have to expect a build up of particles with small masses. This is the situation for the

![Fig. 2: Lifetimes of interplanetary meteoroids with respect to collisions $r_C$ and Poynting-Robertson effect $r_{PR}$.](image-url)
smaller interplanetary meteoroids. This comparison in terms of collisional loss and gain is shown in Fig.3. We have also computed the radial loss due to the Poynting-Robertson effect which is required in order to maintain a radial density distribution proportional to \( r^{-1.3} \).

VI. Balance between different dynamical effects

Large meteor sized particles \((m \geq 10^{-5} \text{g})\) are dominated by collisional fragmentation. Assuming a radial dependence according \( r^{-1.3} \) and a filling factor \( \epsilon = 0.23 \) (Leinert et al., 1983) then a total of 9 t/s is lost from this size range within 1 AU. This particle population would be depleted on a time scale of \( -10^6 \) years without replenishment from cometary and asteroidal sources (Kresak, 1978). Under steady state conditions most meteor particles are “young”, i.e. they have not been fragmented by collisions and their initial orbits are not much altered by radiation pressure. Only planetary perturbations could distort the initial orbits significantly before the particles break up by catastrophic collisions. Observations of meteor streams support this finding. The flow of meteoritic material in mass and space is demonstrated in Fig.4.

The optically active zodiacal light particles \((10^{-10} \leq m \leq 10^{-5} \text{g})\) are dominated by radiation pressure drag and not by catastrophic disruption. Their lifetimes due to Poynting-Robertson effect range from \(10^6\) years to \(10^4\) years for the smaller particles.

The Poynting-Robertson mass flux through a spherical shell with radius 1 AU is 140 kg/s. This flux is the maximum contribution of debris from the asteroid belt to the zodiacal cloud inside 1 AU. Probably its contribution is much less since collisions among meteoroids also contribute to zodiacal particles outside 1 AU.

From Fig.3 it can be seen that at 1 AU many more particles are gained in the mass range \(10^{-10} \text{g} \) to \(10^{-5} \text{g}\) from collisional break-up of meteor-sized particles than are removed by the Poynting-Robertson effect. About 6 to 8 t/s of these particles are produced inside 1 AU. This compares to only a total of \(-0.3\) t/s which are lost by the Poynting-Robertson effect from the same region of space. This situation is not stable but the zodiacal light particle population presently increases in time (on a time scale of about \(10^4\) years at 1 AU). Time stability of this particle population can only be maintained if we have overestimated the meteoroid flux by more than a factor 10 or if the break-up laws which we have applied are not at all representative for interplanetary meteoroids. Both alternatives are not supported by the data.

Small fragment particles which are generated by a collision between a larger parent meteoroid and another meteoroid will move on unbound trajectories if their reduced potential energy (gravitation minus radiation pressure) is exceeded by their kinetic energy which is derived from the parent particle. This is especially effective at the perihelion of an eccentric particle’s orbit, where the kinetic energy and the collision rate are highest. Since the eccen-

![Fig.3: Net mass loss and gain rates from collisions and transport losses due to Poynting-Robertson effect at 1 AU. The total mass lost by collisions \((m \geq 10^{-5} \text{g})\) and gained as fragments \((m < 10^{-5} \text{g})\) is \(9 \times 10^{-9} \text{g}/\text{m}^2\). The Poynting-Robertson effect requires a loss of only \(4.1 \times 10^{-9} \text{g}/\text{m}^2\) in order to maintain the spatial density \(-r^{-1.3}\).](image)

![Fig.4: Schematic diagram of dynamical effects which change mass and heliocentric distance of interplanetary meteoroids. Sources for meteoroids are comets and asteroids, sinks are the ejection from the solar system (\(\beta\)-meteoroids which eventually become interstellar grains) and the evaporation near the sun (this material is ionized and carried away with the solar wind).](image)
tricities of the parent particles are significant even fragment particles of masses as large as \( m - 10^{-10} \) g can get on hyperbolic trajectories and become \( \beta \)-meteors (Zook and Berg, 1975). This direct injection of fragment particles into hyperbolic orbits is a very efficient loss mechanism since the time these particles spend in the inner solar system is only order of 100 days. Therefore, most particles of masses \( \leq 10^{-10} \) g which are produced from the disruption of larger meteoroids can efficiently be removed by this effect. Hence we conclude that the small particle population is in time stability. About 1 to 3 t/s of \( \beta \)-meteoroids pass the Earth's orbit.

References


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D I S C U S S I O N

Giese: There is a debate going on whether one can take the intensity change of zodiacal light with location of the Helios s/c really as a dependence of number density $n \propto r^{-p}$ on solar distance $r$ or not. Since only the product $n \sigma$ can be derived ($\sigma$ is the average differential scattering cross section), a local change of $\sigma$ could make a law $n \propto r$ acceptable. What would be in this case the consequences for your model?

Grün: There are reasons to believe that the scattering does not change too much with $r$: Helios did not see any change in the colour of zodiacal light. However, polarization data indicate some change in the particle properties which may or may not have the effect to change the scattering properties in the sense required to decrease the exponent $a$ of the radial density distribution. Therefore I do not believe that the density distribution $n \propto r^{-a}$ has an exponent $a$ as low as 1. But if we assume, for an exercise, that $a = 1$, then I can show that this leads to a contradiction. A distribution with $a = 1$ would be set up by Pointing-Robertson effect alone. Since we know from the size distribution that zodiacal light particles are not much affected by collisions, no extra source for these particles inside 1 AU is allowed, and all the zodiacal-light particles would originate from outside the Earth's orbit. On the other hand, we know from our calculations of the collisional balance that zodiacal light particles are produced in great abundance from collisions of larger particles. This contradicts sharply the conclusion we derived from $a = 1$ value.

Olsson-Steel: I believe that in fact the true flux of meteoroids (masses $10^{-6}$ - $10^{-8}$ gm) is 20 or 30 times higher than we have thought until now (paper to be presented at this meeting). This would imply a much higher supply to the zodiacal dust cloud.

Grün: No. We have used only the mass slope from meteor data, not the absolute value. The slope nicely fits the slope derived from the lunar microcrater distribution. Because of this close fit, I believe we have used the right meteor flux.
THE CONTRIBUTION OF PERIODIC COMETS TO THE ZODIACAL CLOUD

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The dust production rates of all the known periodic comets, calibrated by the measurements from the 1986 apparition of comet Halley, are used to compute their dust input into the region inside the earth orbit, and the resulting dust fluxes at R = 1 AU. The spatial distribution of the fresh ejecta and the temporal variations of their accumulation are reconstructed. The visible release of dust is evidently insufficient to maintain the zodiacal cloud in equilibrium. It is suggested that the progressive decay of the dark matter, including extinct cometary nuclei, their fragments, and products of asteroidal collisions, represents the dominant source of replenishment of the interplanetary dust complex.

1. INTRODUCTION

The cometary activity is the only directly observable source of the interplanetary dust. Its efficiency depends not only on the dust production by individual comets but also on their revolution periods. When the period is long, essentially all the smaller dust particles are removed immediately from the solar system on hyperbolic orbits by the solar radiation pressure and what remains, spends only a small fraction of each revolution within the inner planetary region. Therefore, the share of the periodic comets (P < 200 yr) should be decisive for the maintenance of the zodiacal cloud, consisting of short-lived dust particles. The earlier estimates (Whipple, 1967; Delsemme, 1976a; Rässer, 1976; Kresáč, 1980) have indicated that the present population of periodic comets is entirely insufficient to maintain the zodiacal cloud in equilibrium. Various possibilities were suggested to explain this discrepancy (as summarized by Delsemme, 1976a), and the long-term stability of the cloud was seriously questioned.

The 1986 apparition of comet Halley has made it possible to estimate the mass loss rates of comets more reliably than before. In a previous paper (Kresáč and Kresáčková, 1987a - thereafter referred to as Paper I) we have computed the mass loss rates of all the known periodic comets over the last two centuries. In the present paper we concentrate on their dust input close to, and inside of, the earth orbit, where the zodiacal cloud is densest. The estimation of the current dust input by individual comets, its variability, and the reconstruction of the resulting spatial distribution of the fresh dust particles can be used not only to check their contribution to the zodiacal cloud but also to judge, by comparison, about the nature of the other sources.

2. CALCULATION OF THE DUST INPUT

The estimates of the mass loss rates of individual periodic comets, as presented in Paper I, were based on some simplifying assumptions which must be reiterated. It was assumed that the mass loss rate of each object is proportional to its total brightness, that both of these quantities vary with the inverse fourth power of the heliocentric distance, and that the gas-to-dust ratio is uniformly equal to the inverse fourth power of the heliocentric distance; anrt that the gas-to-dust ratio is uniformly the inverse fourth power of the heliocentric distance; that both of these quantities vary with the time in the individual comet apparitions (Kresáč and Kresáčková, 1987b - thereafter referred to as Paper II) was adopted. In this list, only irregular brightness bursts of limited duration were excluded and counted separately, and empirical corrections for the instrumental effects were applied. For the derivation of the relevant formulae and for the calibration by P/Halley see Papers I and II. Here we shall use for the mean dust production rate D the relation

\[ D = C 10^{-0.4} H^{-1.5} (1-e)^{-2.5} \]

where

- \( H \) is the absolute total magnitude, q the perihelion distance in AU, and \( e \) the eccentricity of the osculating orbit. The calibration factor \( C \) is 1.25 \times 10^{14} \text{ kg per century}, or 3.96 \times 10^4 \text{ kg per second}.

Owing to the low ejection velocities of the dust particles, of the order of 10% of the orbital velocities of their parent comets, one can assume that the initial orbits are identical. In fact, this approximation holds good for larger particles. Smaller particles are repelled by the differential solar radiation pressure into larger orbits of longer revolution period, and below some critical size lost on hyperbolic orbits. Since most of the dust release takes place around the comet's perihelion, the orbits remain essentially unchanged in this region. This effect tends to accelerate the dispersion of the dust particles along the comet's orbit, and thereby also the operation of differential planetary perturbations. It reduces the input of smaller particles, but this does not seem to play a significant role in the case of short-period comets.

Knowing the total dust production rate D, its long-term average contribution to any region passed by the comet can be determined quite easily, being proportional to the fraction of the orbital period spent within it. For a heliocentric spherical shell with inner radius \( R_1 \) and outer radius \( R_2 \), the conversion factor is proportional to the difference in the mean anomaly of the two crossing points, i.e., \( \left( \omega_M - \omega_N \right) / 180^\circ \). The mean anomalies can be computed in the usual way from the true anomalies, defined by the equation of the orbital ellipse as a function of \( q, e, \omega \) and \( H \). The angular elements \( \alpha, \omega \) and \( i \) also define the positions of the pairs of crossing points, with the true anomaly as the variable depending on \( R \). The flux of dust at these points is given by the dust production divided by the revolution period.

In order to get insight into the temporal variations of these quantities, they were computed, for each comet, for three equidistant epochs: 1800.0, 1900.0, and 2000.0. All the comets are 200 years observed between 1785 and 1985, with q < 1.1 AU at the date in question, were included. For the comets of Jupiter family (P < 20 yr), the oscillating orbital elements were taken from the integrations by Bulava et al. (1986). The only exceptions were P/Pons-Winnecke in 1800 and P/Gregg-Skjellum in.
Table 1

Comet

3 P/Encke
29 P/Grigg-Skjellerup
21 P/Tuttle-Giacobini-Kresak
504 P/Blanpain
73 P/Schwassmann-Wachmann 3
6 P/Brorsen
9 P/Pons-Winneoke
4 P/Biela
71 P/Denning-Pujikawa
8 P/Tuttle
11 P/Crommelin
2 P/Temp^l-Tuttle
505 P/Pons-Gambart
519 P/Dubiago
1't P/Pons-Brooks
27 P/Brorsen-Metcalf
506 P/DeVico
1 P/Halley
507 P/Swift-Tuttle
517 P/Mellish
38 P/Herscnel-fiigollet
520 P/Wilk

1.0

3.31
4.82
5.19
5.26
5.27
5.28
5.71
6.71
9.20
13.78

28.1
33. r

5".5
J9.3

72.6
73.1
75.2
76.3
115.3
142.3
162.3
199.3

0.340
0.732
1.098
0.952
0.960
0.808
0.822
0.901
0.793
1.036
0.753
0.974
0.807
1.095
0.777
0. i85
0.665
0.587
0.982
0.187
0.749
0.633

P/Encke
P/Grigg-Skjellerup
P/Blanpain
P/Brorsen
P/Honda-Mrkos-Pajdusakova
P/Schwassmann-Wachmann 3
P/Tritton
P/Pons-Winnecke
P/Giacobini-Zznner
P/Finlay
P/Biela
P/Denning-Fujikawa
P/Tuttle
P/Crommelin
P/Tempel-Tuttle
P/Pons-Gambart
P/Pons-Brooks
P/Brorsen-Metcaif
P/DeVico
P/Halley
P/Swift-Tuttle
P/Mellish
P/Herschel-Rigollet
P/Wi]k

3.30
4.83
5.16
5.45
5.46
5.55
5.55
5.83
6.47
6.56
6.67
8.83
13.62
27.5
33.4
57.8
71.7
72.0
73.9
76.1
120.0
145.4
154.9
187.4

0.341
0.752
0.953
0.588
0.610
1.069
1.078
0.923
0.932
0.969
0.860

10994

3003

1604

1541

1485

1440

5
93

22

6

10

8.3

86
3

189

5
—
189
7

7

11
104

5
4
156
6

94

360
282

103

121

238

85
241

103

179

0
83
1

1

3

3

7
__

1
40
2
2
2
0

2
0

2

5

113
14
21

39
4
6

28

32
2

47

33

2

2

4

4

5

6

6

714

212

119

121

128

9

15
5

9

217
__

105

9
37

144
—

5

5

5

4

4

0
0

0
0

0
0

0
0

11 .8A

8.6
8.6
7.1
13 . 1A
6 .9
9 .7
8

P/Encke
P/Grigg-Skjellerup
P/Honda-Mrkos-Pajdusakova
P/Schwassmann-Wachmann 3
P/Tuttle-Giacobini-Kresak
P/Wirtanen
P/Giai.obini-Zinner
P/Finlay
P/Denning-Fujikawa
P/Tuttle
P/Crommelin
P/Tempel-Tuttle
P/Pons-Gambart
P/Brorsen~Metcalf
P/Pons-Brooks
P/DeVico
P/Halley
P/Swlft-Tuttle
P/Mellish
P/Herschel-Rigollet
P/Wilk
2000 - Total

3.30

5.11
5.26
5.35
5.44
5.45
6.61
6.76
9.05
13.60

27.7
33.1
56.4
69.9
71.2
74.9
76.0
124.6
153.9
154.9
187.4

82
222
1

8C
7
12
22

7,4
8,.7A
3
4,.0
443
47
7..7
6..3
76
2.,8E 2550
170
3..9
284
7..6
6
7..9
2
9.,4
8.9
11..8
10. 3B
9. 5C
10.,8
11. 8

7.4

7

508
2

5
3

4
113
91
210

2

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3

0

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1642

1645

1550

898
6
14
83

6303

1721

920

LS4

852

826

812

7

8
31

10
—

12

826
__

62
18
—
—
113

65
19
—

72
22
-—
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110
40
—
—

49
—
—
—

23
2

7
47

29
31
358
99
—

8
17

26

96
27

61
18

3
8
51

12

5

26
37

113
52
51

36

65
33
58

28

73

26

26

5

10

3
27
3

3
64
2

3

3

3

106
14

2
2
36
4

2
27
2

2
30
2

22

7

4

716

212

119

4
122

12
34
1
0

9

12
5
0
0

12

1474
491

58
11

3

7

25

12
0
0

10. 1
13. 1
8.1

10
1
29

25
6
9
34
308

8. 1

__

2103

8.9

8.3
9.0
8.4B

2

2655

919
5
33
5
19

1.033
0.791
1,030
0.747
0.975
0.822
0.483
0.781
0.660
0.587
0.959
0.197
0.748
0.619

0

2468

2335

8.7

1
__
2

3872

8045

1.034

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13287

3363

9.8D

__
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5862

479
4
28
4
167
45
31

11. 0
11. 6

.—

13
0
0

4813

9.6
11. 5

0.339
0.996
0.529
0.938
1.054
1.060

2

1438

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508
1

1415

0
0

8.8
15
8.2
12
22
4
7.
411
4.1
48
7.7
6.3
77
2. 8B 2550
171
3.9
7.6
265
7.9
6
2
9.4

1900 - Total
3
29
46
73
21
48
24
17
71
8
11
2
505
27
14
506
1
507
517
38
520

0.7 0.6

1568

8.3

10.6A
8.9
9.4
8.9
9.5C
0.748 11. 4D
1.014
0.739
0.973
0.810
0.776
0.484
0.664
0.587
0.963
0.190
0.748
0.619

0.8

12 .2
10 .4A

1800 - Total
3
29
504
6
46
73
533
9
24
17
4
71
8
11
2
jO5
14
g"7
50b
1
507
517
38
520

0.9

4.4
6.3B
77
2. 8B 2555
3.9
167
229
7.6
8.3
4
2
9- 4
4214

266

3

12
20

52
51
35
3

—
—

32
2

2

6
144

6
219

4
0
0

4
—

4
—

1440

1131

1194

471
3

1177
454
—

440
—

432
—

20
—
—
—
—
—
1
—

21
—
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6
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2
22

25
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-—
—
—
—
—
—
—
2
—
220
—

103
—

3
—
0

3
—
—

689

587

10
1
14

22
0
30

18

6

4

5

1
3

1
1

1

11
80
21

3
27
7
213

2
1
2
20

1

2

2
2

—
—
0
—

7
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—

4

4

35
5

120
11

122
12

128
—

6
145
—

23

28

8
9

4

4

4

3

1
0

0
0

0
0

0
0

0
0

0
0

4397

1364

957

679

656

647

12

—
—

0
0

—
2
—

718

—
—

0
0

39
99
69

53

5

5
—
5
—
—

_-.
-—

5

30

7

2

—
—

128
—
4

20
10
—
—
—
—
1
—

1£5
10

—
_—
37
4
—
3
—
4
44

0

103

4
—
-985
439
—
39
—
—
_—
—
—
—
---3
—

6


Before the respective epoch - H from the preceding was adopted. B, the comet was lost more than 50 yr after the respective epoch - H from the next epoch was adopted (P/Halley).

The variations of the dust input are small for the comets of Halley type, the revolution periods of which are comparable with the period covered by the computations, and orbits rather stable. For typical comets of Jupiter family a drop by a factor of 10 between 1800 and 2000 is indicated, with the reservation mentioned above. This reflects not only the disappearance of P/Biela and P/Brorsen, which were very active in the 19th century, but also the orbital changes of other comets by planetary perturbations. In fact, one half of such comets has changed during each century. Integrations over 800 years (Carusi et al., 1985) show that only three comets of P < 20 yr have remained within q = 1 all the time: the exceptional P/Encke, the extinct P/Brorsen, and the absolutely faintest P/Denning-Fujikawa, with spectacular intermissions of activity (Kresák, 1986). Another 15 comets were passing through q = 1 every 150 years, on the average. For those captured into a temporary libration around the 2:1 resonance with Jupiter, like P/Pons-Winnecke or P/Halley, the duration of activity (Kresák, 1986) shows that the comet was first discovered more than 50 years after the respective epoch - H from the next epoch was adopted in the case of one missed return, + 1 mag after two missed returns, + 2 mag after four missed returns, and the progressive fading it makes a ratio of 2:1 over 200 years! The values for 2000 will be probably subject to some correction upwards by the contribution of some comets so far undiscovered - and also by that of P/Hartley 2 and P/Machholz, discovered in 1986.

2000, because these comets were passing close to Jupiter at that time, so that their osculating elements were not representative for the perihelion passages around which most of the mass loss occurs. Here the elements were replaced by those for the closest 5000-day Julian Date, according to the integrations by Carusi et al. (1983). For the comets of Halley type (20 yr < P < 200 yr) the osculating elements for the nearest perihelion passage were used, since otherwise the difference between the heliocentric and barycentric motion (Carusi et al., 1986) would become significant. For the absolute magnitudes the same basic data as in Papers I and II were used. The weighted means from all observed revolutions falling at least partially within ± 50 years of the epoch in question were adopted. Exceptions from this rule are marked by letters in Table I.

The results of our computations are presented in Table I. It lists, in succession for the three basic epochs and in the order of increasing orbital periods, the following quantities: the name of the comet preceded by its number in the catalogues by Carusi et al. (1983) and Belyaev et al. (1986); the revolution period P, in years; the perihelion distance q, in AU; the absolute total magnitude H; the mean dust production D, in 10^3 kg/century; the mean dust input I(1) into the heliocentric sphere of 1 AU radius, in 10^6 kg/century; the mean dust flux F from this production through the heliocentric spherical surface of radius R > q and < Q, in kg/s; and the mean dust input into spherical shells between R = 1.1 and 1.0 AU, 1.0 and 0.9 AU, etc. The letters added to H have the following meaning: A, the comet was first discovered more than 50 years after the respective epoch - H from the next epoch was adopted. B, the comet was lost more than 50 yr before the respective epoch - H from the preceding epoch was adopted in the case of one missed return, a correction of + 1 mag applied after two missed returns, + 2 mag after four missed returns, and the total dust input inside the earth orbit and in the dust flux through R = 1 AU much smaller, only a little over 10%. Their actual contribution is further reduced by a higher size limit for the p-particles eliminated by the solar radiation pressure. Here comet Encke clearly dominates, providing 80% of the input and 77% of the flux. The progressive fading of this comet, accompanied by a decrease of its dust production, results in an appreciable decline of all of these parameters. In the total input and flux it makes a ratio of 2:1 over 200 years! The values for 2000 will be probably subject to some correction upwards by the contribution of some comets so far undiscovered - and also by that of P/Hartley 2 and P/Machholz, discovered in 1986.

Table I - continued

<table>
<thead>
<tr>
<th>Comet</th>
<th>0.5</th>
<th>0.4</th>
<th>0.3</th>
<th>0.2</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 P/Encke</td>
<td>1630</td>
<td>2045</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>27 P/Brorsen-Metcalf</td>
<td>2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>517 P/Mellish</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1800 - Total</th>
<th>1636</th>
<th>2049</th>
<th>--</th>
<th>--</th>
<th>--</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 P/Encke</td>
<td>938</td>
<td>1165</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>27 P/Brorsen-Metcalf</td>
<td>2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>517 P/Mellish</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1900 - Total</th>
<th>944</th>
<th>1169</th>
<th>--</th>
<th>--</th>
<th>--</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 P/Encke</td>
<td>496</td>
<td>631</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>27 P/Brorsen-Metcalf</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>517 P/Mellish</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2000 - Total</th>
<th>500</th>
<th>634</th>
<th>--</th>
<th>--</th>
<th>--</th>
</tr>
</thead>
</table>

The relative contribution of different comets or comet types to their total dust production D, to the dust input into the region of R < 1 AU and to the dust flux through R = 1 AU is summarized in Table II. OJF means comets of the Jupiter family other than P/Encke, and OHT comets of Halley type other than P/Halley.

While 70% of the dust production fall on the comets of Halley type (and 50% on P/Halley alone) their long orbits make their share in the dust input inside the earth orbit and in the dust flux through R = 1 AU much smaller, only a little over 10%. Their actual contribution is further reduced by a higher size limit for the p-particles eliminated by the solar radiation pressure. Here comet Encke clearly dominates, providing 80% of the input and 77% of the flux. The progressive fading of this comet, accompanied by a decrease of its dust production, results in an appreciable decline of all of these parameters. In the total input and flux it makes a ratio of 2:1 over 200 years! The values for 2000 will be probably subject to some correction upwards by the contribution of some comets so far undiscovered - and also by that of P/Hartley 2 and P/Machholz, discovered in 1986.

Table II

<table>
<thead>
<tr>
<th>Comet</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>P/Encke</td>
<td>OJF</td>
</tr>
<tr>
<td>P/Halley</td>
<td>OHT</td>
</tr>
</tbody>
</table>

| Total dust production D : |                      |
| 1800 | 134 kg/s       | 11.4 | 7.6  | 60.6 | 20.4 |
| 1900 | 153 kg/s       | 15.7 | 9.8  | 51.4 | 19.9 |
| 2000 | 157 kg/s       | 19.8 | 8.9  | 51.4 | 19.9 |

| Dust input I(1) into R < 1 : |                      |
| 1800 | 0.5 kg/s       | 26.7 | 11.5 | 43.5 | 18.3 |
| 1900 | 0.7 kg/s       | 28.3 | 10.2 | 8.9  | 2.6  |
| 2000 | 0.5 kg/s       | 26.5 | 3.2  | 16.3 | 4.0  |

| Mean | 0.7 kg/s       | 26.5 | 3.2  | 16.3 | 4.0  |

| Dust flux F(1) through R = 1 |                      |
| 1800 | 2.0 kg/s/yr    | 27.6 | 13.8 | 5.6  | 2.0  |
| 1900 | 1.7 kg/s/yr    | 27.2 | 12.6 | 9.2  | 3.3  |
| 2000 | 1.2 kg/s/yr    | 27.4 | 3.6  | 17.2 | 5.0  |

| Mean | 1.4 kg/s/yr    | 27.2 | 3.6  | 17.2 | 5.0  |

The variations of the dust input are small for the comets of Halley type, the revolution periods of which are comparable with the period covered by the computations, and orbits rather stable. For typical comets of Jupiter family a drop by a factor of 10 between 1800 and 2000 is indicated, with the reservation mentioned above. This reflects not only the disappearance of P/Biela and P/Brorsen, which were very active in the 19th century, but also the orbital changes of other comets by planetary perturbations. In fact, one half of such comets has changed during each century. Integrations over 800 years (Carusi et al., 1985) show that only three comets of P < 20 yr have remained within q < 1 all the time: the exceptional P/Encke, the extinct P/Brorsen, and the absolutely faintest P/Denning-Fujikawa, with spectacular intermissions of activity (Kresák, 1986). Another 15 comets were passing through q = 1 every 150 years, on the average. For those captured into a temporary libration around the 2:1 resonance with Jupiter, like P/Pons-Winnecke or P/Halley, the passages in and out recur rather periodically.

The differences between the two types of periodic comets in the rate of orbital evolution imply a substantial difference in the wandering of the crossing points on the sphere of R = 1 AU. While those of the Halley type are relatively stable,
those of the Jupiter family can suddenly skip over
tens of degrees. This problem, essential for the
recurrence of meteor showers, will be discussed in
more detail elsewhere (Kresák and Kresáková, in
preparation). However, one important point must be
stressed here. The comets of the Jupiter family
tend to produce strong temporary meteor showers at
the time when one of the crossing points passes the
plane of ecliptic but, except of P/Encke, they do
not produce permanent showers farther from the pas-
sage, like some comets of Halley type (P/Halley,
P/Swift-Tuttle, P/Temple-Tuttle). Hence, it appears
improbable that any of them could have made a sub-
stantial contribution to the maintenance of the
zodiacal cloud in the past.

4. THE SPATIAL DISTRIBUTION

By summing up the I(R) values from Table 1, and
dividing them by the volumes of the 0.1 AU broad
spherical shells, the variations of the dust input
with heliocentric distance can be reconstructed.

In Figure 1 these are compared with the $R^{-1.3}$ de-
pendence of the spatial density of the dust, as deter-
mined by Alten et al. (1985) from the measure-
ments on the Helios space probes. The agreement
is unexpectedly good, but only thanks to the domi-
nant contribution of P/Encke. When this comet is
omitted, any dependence on R vanishes in irregular
fluctuations, produced by local enhancements in
the ranges where the most productive comets pass
their perihelia. The lower part of the figure as-
sumes an oversimplified model in which the orbits
are not liable to perturbations, and each comet
has the same initial dust supply (i.e., lifetime
inversely proportional to the dust production
rate). In spite of the minor peak at the perihel-
on, the general trend, resembling an
dependence, is absolutely irreconcilable with
the observations. This failure underlines the im-
portance of some effects neglected in this simpli-
fication, or all of them: the broad variety in the
initial dust supply of different comets; the oper-
ation of planetary perturbations, increasing the
dust production rate after each reduction of the
perihelion distance, and vice versa; the transfer
of the dust particles inwards by the Poynting-
Robertson drag; and their decay at smaller helio-
centric distances. Unfortunately, the available
data do not allow to assess the relative impor-
tance of these effects in their compound operation
resulting in the observed increase of the density
towards the Sun. For the innermost region we have
practically no observational evidence, and only
one periodic comet (P/Mellish) passes through R
= 0.2 AU. Another case, not included in our computa-
tions, is the recently discovered P/Machholz.

The distribution of the dust input with respect
to the ecliptical plane can be determined from the
distribution of the points in which the individual
orbits cross the heliocentric spheres of varying
R. In Figure 2 two alternatives are compared, one
based just on the number of crossing points, and
the other with each crossing point weighted by the
computed dust flux through it. Absolute values of
the latitudes are used, since the distribution is
roughly symmetrical with respect to the ecliptic.
The two solutions are in excellent agreement, ap-
parently due to the fact that the inclination of the
orbit of P/Encke is rather typical for short-
period comets.

Figure 1. Above, the relative dust input $I_R$, re-
ferred to the average at $R < 1$ AU, as a function of
the heliocentric distance $R$. Below, the same assum-
ing an equal dust production for all comets. Open
circles, all comets; full circles, P/Encke omitted.
The circled areas are proportional to the inputs
on which the data are based. The full curve corre-
sponds to $I_R \propto R^{-1.3}$, the dashed one to $I_R \propto R^2$.

Figure 2. The medians of the absolute ecliptical
latitudes $B$ of crossing points with the sphere of the
$R = 1$ AU, as a function of the heliocentric dis-
tance $R$. Open circles, data weighted by the fluxes
$P$ through these points; full circles, each cros-
sing point counted once. The circled areas are
proportional to the total fluxes, and to the num-
ers of points included, respectively.
One half of the total dust input is concentrated within ± 12.5° of the ecliptical plane, irrespectively of the heliocentric distance. This alleviates the reconstruction of the distribution perpendicular to this plane, as all the crossing points can be taken together. The results are presented in Figure 3, separately for the comets of the Jupiter family, those of Halley type, and all comets. There is no weighting by the dust input, but the summation of the data from three epochs and from heliocentric spheres 0.1 AU apart makes the weights of individual comets roughly proportional to their average path length within R = 1 AU.

For a spherically symmetrical distribution, the cumulative numbers of the crossing points should follow the dashed diagonal. This is reached by adjusting the horizontal scale to x = sin B, and fitting the vertical scale to the population at low latitudes. The data points follow the diagonal rather closely up to B = 15° for the Jupiter family and up to B = 28° for the comets of Halley type. Then a steep drop appears in both samples. A comparison with the percentages on the left-hand scale shows that the dust input into the zone around the ecliptic is 3.6 times larger than its overall value for the Jupiter family, but only 1.5 times larger for the comets of Halley type. For all the comets taken together the ratio is 2.3, and the trend can be tentatively reconstructed, as indicated by the dotted line. The drop of the density is steep indeed: from 100 % at B = 15° to 50 % around B = 20°, 30 % around B = 30° and 20 % around B = 40° to 15 % at B = 50°.

The distribution in longitude is rather irregular. At R = 1 AU, P/Encke and P/Halley enhance the density in the first and third quadrant, producing an oblong shape of the cloud. The distribution at smaller heliocentric distances is governed by the perihelion arc of the orbit of P/Encke in the second and third quadrant.

5. CONCLUSIONS

The dust productions, inputs and fluxes given in Tables I and II are still subject to considerable uncertainties. Just the uncertainties in the absolute magnitudes of individual comets may account for differences of tens of percent in the computed values, and the lightcurve irregularities add to this. There may be significant departures from the adopted R-1 dependence of the brightness, and the dust production may follow a different law. Recent observations of P/Halley and other comets have demonstrated that the dust release tends to occur in irregular jets, and that the dust-to-gas ratio varies appreciably. The main source of uncertainty is the limitation of observational evidence to smaller dust particles which are not decisive for the total mass loss. The extrapolation to higher size ranges is still an open problem (McDonnell et al., 1986). For these reasons our numerical data must be taken with caution, in particular where they are given, for the sake of conformity, to more significant digits. The existing estimates of the mass of the zodiacal cloud and its rate of replenishment are very approximate, too.

In spite of these limitations, the evaluation of the present contribution of periodic comets to the zodiacal cloud implies some general conclusions. In each century, there are only about 15 to 20 active comets ejecting dust at R < 1 AU, with revolution periods less than 200 years. Their individual input...
rates cover a range of four orders of magnitude, 95% of the total falling on about 5 objects only. For the last two centuries, P/Encke dominated the dust input into the interplanetary dust cloud by 80% of the total, followed by P/Halley with 8%. The next two comets, P/Brosen and P/Biela with 2 to 3% each, have already disappeared more than 100 years ago, although they were bright at their last apparitions and P/Biela consisted of two active components. It is difficult to believe that the dust input into interplanetary dust has stopped at the moment when they cease to be optically active. This lends support to the viewpoint that the processes in cometary comae are not the only source of dust.

The calibration of the dust production rates by the direct input at the aphelion distance of P/Halley has not shattered the previous conclusion by Whipple (1967) and others, that the ejecta from the present population of periodic comets are unable to maintain the zodiacal cloud in a state of equilibrium. Our results point to appreciable variations of their contribution on a time scale of a few centuries, but the input remains all the time below the needs. When compared with Whipple's round value of \(10^4\) kg/s, the average dust production of all periodic comets makes 2.4%, that of the periodic comets of \(q < 1\) AU 1.6%, and the direct input into \(R < 1\) AU 0.03%, indicating that the intensity of the dust production rate shows no appreciable increase with increasing heliocentric distance, following very closely the \(R^{-1.3}\) dependence found by Leinert et al. (1981), appears. This also expands the equlidity lines, pointing radially from the Sun, into a shape consistent with the narrow single-lobe model. This is in conflict with all the observational evidence, as summarized by Giese et al. (1986). When P/Encke is included, however, the situation changes drastically. A decrease of the density with heliocentric distance - following very closely the \(R^{-1.3}\) dependence found by Leinert et al. (1981), appears. This also expands the equlidity lines, pointing radially from the Sun, into a shape consistent with the current models.

So there is strong circumstantial evidence in support of the idea, first expressed by Whipple (1967) that P/Encke is the main source of maintenance of the zodiacal cloud. There are only two objections. First, P/Encke presents itself as a comet with an extremely low dust-to-gas ratio, and its dust production rate shows no appreciable increase at all solar distances, in contrast to the Newburn and Spinrad (1985). And second, searches for records of its earlier apparitions - when it should have been very bright if its secular brightness decrease is extrapolated back - remained without success (see Whipple and Hamid, 1972). On the other hand, there are uniquely broad streams of larger meteor particles, some of them hardly discernible from the sporadic background, which are apparently genetically associated with this comet (Stöhl, 1985; Porubčan and Stohl, this Volume). Several large asteroidal objects were found to revolve in similar orbits (Napiér et al. 1983), and the association of the Tunguska impact also appears very probable (Kresák, 1978). From the dynamical point of view it is clear that decoupling of the aphelion of P/Encke from Jupiter would have required a long or strong operation of nonspherical effects, which also points to a much larger size and dust supply of the parent body.

Whatever may be the share of P/Encke, or of the family of objects associated with it, in building up the zodiacal cloud, it appears almost certain that the dark matter, not involved in the optical display of cometary activity, is a fundamental role here. The parent bodies may range from larger objects like 3200 Phaethon and cometary nuclei experiencing a dormant phase (Kresák, 1986), through extinct remnants and fragments of cometary nuclei, to meteorite- and meteoroid-sized objects disintegrating gradually into dust. Observable splitting of periodic cometary comae and their extinction into interplanetary dust have stopped at the moment when they cease to be optically active. This lends support to the viewpoint that the processes in cometary comae are not the only source of dust.

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DISCUSSION

Shulman: I do not understand how you have estimated the dust production of comet Encke, because nobody has ever seen any traces of continuum in its spectra.

Krerak: We have assumed the same dust-to-gas ratio for all periodic comets, because the present information on a great majority of such objects is very limited. Also, the size distribution of the released dust particles may substantially differ from one comet to another. P/Encke is indeed a gaseous object according to optical observations. On the other hand, there are uniquely broad streams of meteoroids associated with it, which points to a substantial contribution of the solid component to the total mass loss.

Fechtig: I think one should also expect large particles from long-period comets, which then could be the targets for dust production by collisions.

Kresak: This is certainly true, but the proportion of such objects should be very limited. This is evidenced by their low proportion among the meteors - in spite of the high luminous and ionizing efficiency at their high geocentric velocities - and also by the oblateness of the zodiacal cloud.

Görn: What do you mean by the dust production rate? We know, at least from the Halley in situ measurements, that much mass is carried by large particles > 10^3 g, which are invisible to other methods (except meteor studies). Most of these large particles move on orbits very close to the parent comet and therefore are not lost. As pointed out by Dr. Crifo, the uncertainty of the dust to gas mass ratio is large (0.3 to 20), because of the uncertainty of the large particle production.

Kresak: Our results are based on the assumption of 1:3 dust-to-gas ratio, as an average estimate from the in situ measurements of P/Halley (see e.g. Whipple, ESA SP-250/II, 281). The larger particles, undetectable due to their low optical efficiency and low impact rate, are included in what we call the dark matter. The disproportion between the required and observed input implies a dominant share of larger solid objects, liable to further desintegration. I think we agree on this point.

Hajduk: A comment in connection with Dr. Shulman's question: There is no doubt that large particles are released from P/Encke, as we observe them in the huge complex of Taurid showers. The contribution of these particles to dust/gas ratio depends on the mass distribution index and its evolution (Porubčan and Štohl, TS-2, this meeting; Hajduk A. and Kapišinski I.: ESA SP-278, in press). Olsson-Steel: Isn't the simplest solution to the problem of non-balance (apparently) between cometary dust production, the meteoroid flux, and the supply to the zodiacal cloud, a hypothesis that the present complex is not in a steady-state? (i.e. many more comets × 10^7 to 10^8 years ago).

Kresak: I have mentioned that just within the last two centuries there was a change by a factor of three. Certainly, temporal variations of much larger amplitude may occur, but these should be due to the contribution of exceptional objects rather than to the varying number of comets involved. Anyway, there is strong circumstantial evidence for the dominant role of the dark matter, which we do not observe in cometary comae and tails.
Kinetic equations for the distribution function of dust particles in mass and element spaces are formulated. Erosive as well as catastrophic collisions are taken into account. Sputtering is also included and radiative effects are considered. Initial conditions are derived from the Interplanetary Flux Model for mass distribution, and fan or cosine models for spatial density.

Introduction

Stability of the Interplanetary Dust Complex was recently considered in the very comprehensive review by Grün et al., (1985). In the most probable evolutionary scenario that was found by comparing collisional gain and loss rates in different mass intervals the spatial density of small particles would increase on account of fragmentation of large particles. Pointing-Robertson effect is not strong enough to compete with collisions in determining spatial density. It is interesting to find how fast will evolve spatial densities of particles of different sizes and whether the steady state could be obtained for some distribution of sources. The second question immediately follows: will initially independent mass and spatial distribution functions couple during the evolution?

To solve this problem one has to construct a kinetic equation for distribution function of particles in space and mass domains. Some knowledge of the initial velocity distribution function is needed. The most important effects that should be included into the equation are: gravitational attraction of the Sun, radiation pressure, Pointing-Robertson effect, collisions: catastrophic and erosive, solar wind sputtering. We ignore, in this paper, Lorentz scattering and planetary perturbations, as there is no common agreement on the importance of these effects.

Kinetic equation

usually a kinetic equation is formulated and solved in the phase-space of coordinates and velocities. In case of interplanetary dust there are reasons to use the space of elements. First, we can easily eliminate the variables on which the distribution function should not depend: \( \omega, Q, M \). These elements are randomized due to the action of planets and more or less uniform distribution of solar wind sputtering. In case of interplanetary drift and orbital perturbations, evolution pressure force are implicitly included in the concept of Keplerian elements, while the Pointing-Robertson effect averaged over orbital period is given by the well known formulae of Wyatt and Whipple (1950) in the \((a,e)\) variables. The most difficult task is to describe collisions in the space of elements. However the probability of collisions between two groups of particles with given \((a,e)\) and random values of remaining elements was obtained in the papers by Kessler (1981) and Steel and Baggeley (1985). We will use their formulae to generate collisional terms in the kinetic equation.

the distribution function \( h(m, a, e, i, t_0) \) can be found from the known space - \( n(r, \beta) \) and mass \(-N(m)\) distributions. We assume that they are independent and that \( n(r, \beta) \) separates into two distributions: \( n_1(r) \) depending on heliocentric distance and \( n_0(\beta) \) which is a function of ecliptic latitude. Hence the distribution function \( h(t=t_0) \) also separates:

\[
 h(m,a,e,i,\beta, t_0) = N(m)f_1(a,e)f_2(\beta) \tag{1}
\]

where \( f_1(a,e) \) and \( f_2(\beta) \) are to be calculated from the integral equations (Haug, 1958):

\[
 n_1(r) = \frac{N_p}{2\pi^3} \frac{1}{r} \int_{\alpha_2}^{\alpha_1} \int_{\varepsilon_2}^{\varepsilon_1} f_1(a,e) \, da \, de \tag{2}
\]

\[
 n_2(\beta) = \frac{\pi^2}{2} \int_{\beta_0}^{\beta_1} \frac{f_2(\beta, i) \, di}{\sin^2 i - \sin^2 \beta} \tag{3}
\]

where \( N_p \) is total number of particles.

We solved the Abel-type equation (3) for the two commonly used distributions \( n_2(\beta) \): fan model \( \sim \exp(-2.1.\sin^2 \beta) \) and cosine model \( \sim 0.15+0.85.\cos^2 \beta \). The obtained distribution functions \( f_2(\beta) \) are presented on Fig. 1. The integral equation (2) has no unique solution. We assumed the power law distribution in major semiaxis independent on the distribution in eccentricity (Leinert et al.,1983)

\[
 f_1(a,e) \sim a^x f_{1e}(e) \tag{4}
\]

and tried to find \( x \) giving the best fit to the observed dependence of \( n_1(r) \) at \( r=0.3 \). 

For the exponential function \( f_1=e^{\exp(-e)}, \) we obtained \( x=0.85 \) that gives dependence \( r^{-1.7} \) at \( r=0.2 \) AU and \( r^{-1.3} \) at \( r=0.3 \) AU. For the Rayleigh distribution \( f_{1e}(e)=e^{\exp(-2e^2)} \) which has a maximum at \( e=0.5 \) and can be close to the distribution of sources (larger meteoroids, comets) we get \( x=0.3 \) and for the heliocentric dependence: \( r^{-1.3} \) at 0.9 AU and \( r^{-1.29} \) at 0.3 AU, Leinert et al. (1983) came to a similar result for the Rayleigh distribution.

Collisions between two groups of particles
Fig. 1. Distribution functions of orbit inclinations obtained from two model distributions in ecliptic latitude: fan model and cosine model.

with elements $\{a,e,i\}_1$ and $\{a,e,i\}_2$ take place in a torus $T$ with the cross-section given by the following inequalities in the $(r, \beta)$ coordinates (Fig. 2):

$$\max(q_1, q_2) = r_{\min} \leq r \leq r_{\max} = \min(q_1, q_2)$$

$$\beta_{\max} \leq \beta \leq \beta_{\max} = \min(i_1, i_2)$$

Collision probability (Steel and Baggaley, 1985) $P_{12}(\{a,e,i\}_1, \{a,e,i\}_2)$ is described by the integral over the torus with the integrand $K(r, \beta)$ proportional to the time of residence of both particles inside the volume element connected with the point $(r, \beta)$.

$$P_{12}(\{a,e,i\}_1, \{a,e,i\}_2) = \int_{T} dr d\beta K(r, \beta)$$

Two kinds of collisions are considered: erosive and catastrophic, the latter one occurring when $m_0 \cdot f_r \geq m_1 \cdot m_2$, $m_0$ being the projectile and target masses, respectively. $f_r$ is a function of the square of the relative velocity of the colliding particles and of the physical properties of the particles: their density and compressive strength $S_c$ (Grün et al., 1985). Mean square of the relative velocity can be found from the formula:

$$\langle v_{rel}^2 \rangle = \int_{V_{rel}} v_{rel}^2 K(r, \beta) dr d\beta$$

where $v_{rel}^2(r, \beta)$ is an average of four possible values.

Mass distributions of the fragments are calculated from the formulae for catastrophic and erosive collisions, respectively (Fujitaka et al., 1977; Dohnanyi, 1978). In the case of isotropic distribution of the velocities of fragments and of the same value of the velocity modulus for all the fragments we get the following value of the fragments velocity in the Center of the Mass System coordinates:

$$v_f^2 = \frac{m_0 \cdot m_2}{(m_0 + m_2)^2} \cdot (\tilde{v}_2 - \tilde{v}_1)^2$$

$$\frac{\partial h}{\partial t} + \text{div}(\mathbf{v}_n \cdot h_n) = \sum_{l,k} c^{\alpha e} h_{nk} (1 - p_{nlk})$$

where $c$ describes inelasticity of collisions ($0 \leq c \leq 1$). Hence, for the collisions with $m_2 \ll m_1$, which are the most probable ones, we can assume that the velocities of fragments are the same as the velocity of their parent body - $m_1$. If two colliding bodies have similar sizes $m_1 \approx m_2$, the spread of fragments velocities is large. This effect leads to mass-elements coupling in the kinetic equation.

Small fragments are removed from the system by the radiation pressure which puts them onto hyperbolic orbits ($\beta$ - micrometeoroids effect). The probability that a fragment becomes a $\beta$-micrometeoroid is equal to:

$$P_\beta = \frac{1}{P_{12}} \int_{r_{\min}}^{r_{\max}} K(r, \beta) dr d\beta$$

where $1 - \frac{1}{c} = \frac{2}{r} \cdot \frac{\tilde{v}_r^2}{\mu_f}$ and $\mu_r = \mu(1 - \beta)$ is the gravity constant reduced by the radiation pressure. $\mu$ is the Newtonian function.

To simplify the equations, instead of a continuous mass distribution following, five values of the particle masses have only been assumed: $10^{-6}$, $10^{-2}$, $10^{-2}$, $10^{-6}$, and $10^{-8}$ for meteoroids, $10^{-10}$ and $10^{-8}$ for $\beta$-micrometeoroids. Special densities of the corresponding particles calculated from the Interplanetary Flux Model (Grün et al., 1985) are as follows:

$$1.7 \times 10^{-21}, 2.9 \times 10^{-16}, 6.4 \times 10^{-12}, 1.6 \times 10^{-9}, 4.9 \times 10^{-8} \text{g cm}^{-3}$$

Kinetic equations for the distribution functions $h_n(a, e, i, t)$, $n=1,...,5$, of the particles are:
where the second term on the left side describes Poynting-Robertson effect. Div operator acts in (a, e, i) space, with $\vec{u}_n$ being the velocity field

$$\frac{da}{dt} = \frac{de}{dt} = \frac{di}{dt}$$

(Wyatt and Whipple, 1950). On the right side following collisional terms are represented: the gain due to catastrophic and erosive collisions of particles with different masses, the gain due to catastrophic collisions between particles with the same mass $[P(e_1, e_1, e_2)$ is the mass-elements coupling function; $e_1 = (a, e, i)]$, the loss due to catastrophic and erosive collisions, the loss due to the sputtering. $G$ and $L$ are functionals depending on the distribution functions of colliding particles, on the collision probability $P_{ii}$ and on the fragmentation function $\psi_{kl}$ which gives the number of $n$-type particles resulting from collisions of particles of $k$ and $l$ types. Mass loss per unit time due to erosion and sputtering is transferred into the number of particles of considered type. Sputtered mass ratio $\frac{dP}{P_{ab}}$ for the $(a, e, i)$ orbit is calculated by its averaging over one orbital period.

The equations can be solved after discretization in the $(a, e, i)$ space.

REFERENCES


DISCUSSION

Grün: I commend you that you took tremendous task to solve meteoroid dynamics both in orbit space and mass space. I have one comment. According to your model the zodiacal particles are fragmentation products of larger meteor particles. Therefore, the orbital distribution you put in the model should be the meteor distribution, and the zodiacal particle distribution should result. An important question is: how different can be both distributions?

Banaszkiewicz: In this paper we have just concentrated on the derivation of the method to be used for further computations. So at the moment I am unable to answer your interesting question.

Kneissel: Did you only take into account prograde orbits?

Banaszkiewicz: Yes. They seem to be the dominant population in the interplanetary dust complex (Leinert, Space Sci. Rev. 118, 281).
Dust particles of sizes between 1 micron and 100 microns from various materials have been contained with help of quadrupole field in vacuum chamber at pressures from 10^{-4} to 10^{-6} mbar and charged by Ar^+ ions of energies up to 3 keV as well as by electrons of energies up to 5 keV. For damping of particles motion at low pressures the damping system with photomultipliers and feedback circuits was developed. By charging with Ar^+ ions charge-to-mass ratios up to 4 C kg^{-1} were measured and dependence of maximum charge-to-mass ratio on the energy of ions was studied. Measurements of parameters of secondary electron emission by charging with electrons at different chamber pressures were started.

There are many cosmic environments where electric charging of dust particles by electrons and ions takes place (see e.g. review of Whipple 1981). The value of charge can have very important consequences for the life time of dust particles and many physical phenomena related to them (e.g. Pechtig et al. 1979; Grün et al. 1984, Mendis et al. 1984). Theoretical calculations of charging are based on many unreliable data and therefore we started experimental work trying to simulate charging processes and improve our knowledge of them.

For charging of particles we used a vacuum chamber similar to one used before by Vedder (1963, 1978). The containment of particles during the charging process is achieved by the three-dimensional electric quadrupole field generated by voltage V-Ucoswt applied to conducting hyperbolic surfaces given in cylindrical coordinates by r^2-z^2=A_0^2, two other hyperbolic surfaces given by r^2-z^2=r^2_0^2 are grounded, see Fig.1. The equation of motion of contained charge particle is then (for details see e.g. Wurker et al. 1959) given by Mathieu's differential equation and its charge-to-mass ratio Q/M is given by

$$Q/M = 2QC_0\frac{\omega_2}{U},$$

where $C_0$ is the rigidity of the suspension system and $\omega_2$ is the angular frequency of motion of contained particles. From this follows that $Q/M$ is the frequency of motion of contained particles in $z$ direction. If $U$ is the potential ions can't overcome the electrostatic surface barrier of the particles.

For test measurements we used particles from glass, amorphous carbon and very loosely bound Al_2O_3 particles with diameters of 10 to 100 µm, 1 to 10 µm and 1 to 30 µm respectively. Their size distributions are shown in Fig.3. These particles were again charged by Ar^+ ions of energies up to 3 keV with intention to reach high values of Q/M. Maximum value of about 4 C kg^{-1} was achieved with Al_2O_3 particles.

Further measurements were done with two samples of spherical glass particles of average diameters 42 µm and 51 µm respectively. Their size distributions are shown in Fig.4. These particles were charged by Ar^+ ions of energies up to 3 keV. The aim was to attain the maximum possible values of Q/M and compare them with the theory. According to theory, the maximum surface electrostatic potential of particles $\phi_{max}$ in volts should be equal to the energy of ions $E_i$ in eV. (At higher surface potentials ions can't overcome the electrostatic surface barrier of the particles). From this follows that

$$Q/M = \frac{3C_0}{2} \phi_{max} - \frac{3\rho\phi}{2E_{max}},$$

where $\rho$ and $r$ are respectively density and radius of the particles, and $C_0$ is the permittivity of vacuum. Typical charging curves (dependencies of Q/M on time) are shown in Fig.4. Dependences of measured (Q/M)_{max} on ion energy for individual particles shows Fig.5. Average values of (Q/M)_{max} as functions of the ion energy for particles from respective samples are shown in Fig.6.
Figure 2. Vertical (left) and horizontal (right) cross section of the electrostatic suspension system.

Figure 3. Size distributions of glass particles with average diameters of 42 μm (left) and 51 μm (right).

Figure 4. Typical charging curves, errors of measurements are about 10%. The maximum charge is reached after about 3 min.
Figure 5. Dependences of $(Q/M)_{\text{max}}$ on ion energy for individual particles

Figure 6. Average values of $(Q/M)_{\text{max}}$ as functions of the ion energy, measured for 27 glass particles of 42 µm (left) and for 31 particles of 51 µm diameter (right). The error bars represent the standard deviation of the $Q/M$-values.

Trying to find influence of the voltage $U$, we charged particles at different $U$ keeping it during the charging process constant. Fig. 7 shows dependence of $(Q/M)_{\text{max}}$ on $E$, in case of a 51 µm particle for different $U$, the theoretical curve is again on the left. From the measurements above follows that the measured values of $(Q/M)_{\text{max}}$ are less than the theoretical ones given by (2). This indicates that “effective energy” of ions (the energy of ions in the center of the suspension system) is equal to the initial energy reduced by some factor which is increasing with the applied voltage $U$.

Particles were also charged by electrons of energies up to 5 keV with main purpose to study secondary electron emission from particles by charging at different chamber pressures and also to determine the influence of rest gas. (At first we wanted to find the yield at different energies of primary electrons which is well known for many materials in case of plane surfaces, but for small particles it has been only roughly estimated up to now). This could be done by determination of the equilibrium surface potentials of particles at different pressures and then by solving the set of equations describing respective equilibrium states. Initial measurements were made with glass particles of diameters of 40 to 50 µm and 50 to 60 µm respectively. For the present only qualitative features have been found, such as that surface potential is always positive, increase (decrease) of pressure or
energy of primary electrons imply increase (decrease) of potential, and that the potential is independent of the flux of primary electrons. We expect that in the future more precise measurements with an improved suspension system will give more definite quantitative results.

References:


THE SYMMETRY PLANE OF THE ZODIACAL CLOUD RETRIEVED FROM IRAS DATA

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and University Paris VI

The annual oscillations of the brightnesses observed at 12 and 25 μm by IRAS near the ecliptic poles are mainly due to the inclination of the symmetry plane (SP) of the interplanetary dust cloud upon the ecliptic, but also, secondarily, to the eccentricity of the earth's orbit.

Comparing the brightnesses at the poles and in the ecliptic (near 90° elongation) allows a retrieval of the inclination i and ascending node ω SP/ecliptic through an inversion technique, with very little model-dependence. The results (i = 1.5°, ω = 90°) conflict with some of those previously obtained from the same observations by more model-dependent approaches, but they agree with former optical determinations from D2A satellite and from Tenerife ground-based data.

1. UNCERTAINTIES ABOUT THE SYMMETRY PLANE OF THE ZODIACAL CLOUD

Several determinations of the inclination, i, and of the ascending node, ω, of the symmetry plane (SP) of the interplanetary dust cloud w.r.t. the ecliptic plane have been published after optical studies of (i) brightness-profile asymmetries, (ii) departures of the peak from ecliptic, (iii) seasonal oscillations of brightness near the ecliptic poles. Figure 1, which summarizes the results of the past two decades:

2. Leinert et al., 1976 (rockets) - first model
2'. Leinert et al., 1976 (rockets) - second model
3. Misconi, 1977; Misconi and Weinberg, 1978 (ground-based observations at Haleakala, Hawaii)
4. Dumont and Levasseur-Regourd, 1978 (ground-based observations at Izña, Tenerife)
5. Dumont and Levasseur-Regourd, 1978 (satellite D2A)
6. Leinert et al., 1980 (Helios space probes)
7. Tanabe et al., 1980 (ground-based observations at Kiso, Japan)
8. Winckler et al., 1985 (ground-based observations at Jungfraujoch, Switzerland)
8'. Winckler et al., 1985 (ground-based observations at La Silla, Chile)
9. Maucherat et al., 1985 (satellite D2B)

The apices of the perpendicular to the SP on the celestial sphere to scatter over more than 4 square-degrees. Part of these discrepancies, however, comes from the elongation-dependence of the heliocentric distance of the most contributing sections of the line-of-sight (los) : Ref. 1a, 2, 2', 3 deal with regions inner to the earth's orbit; Ref. 1a, 4, 5 with regions near it; Ref. 7, 8, 8', 9 with regions outer to it, so that some warping of the SP seems to exist, as pointed out by Misconi 1980. Ref. 6, on the other hand, was claimed to be valid irrespective of the sun's distance.

Also displayed on Fig. 1 are the apices relevant to the recent infrared observations of thermal emission from interplanetary dust (the satellite "IRAS" and the rockets of "ZIP"). In a preliminary study of IRAS data, Hauser et al., 1984, claimed the seasonal oscillations of brightness near the ecliptic poles to be in agreement with optical determinations 3 and 6. In subsequent papers, both the inclination and the node were found to be smaller:

A. Hauser and Gautier, 1984; Rickard et al., 1985; Hauser and Houck, 1985 (seasonal oscillations near the poles)
B. Hauser et al., 1985 (same approach)
B'. Hauser et al., 1985 (departures of the peak from ecliptic)
B''. Hauser et al., 1985 (same approach, with correction suggested in the following ref.)
C. Dermott et al., 1985 (same approach)

Like in the optical case, a shift of the apex (rightwards on Fig. 1) can be seen, as the most contributing sections of the los recede from ~1 AU (Ref. A, B) to more than 1 AU (Ref. B', B'', C).

With these IRAS apices can be compared the apex from ZIP, which admittedly was more uncertain:


2. REDUCTION OF MODEL-DEPENDENCE IN INTERPRETATION OF IRAS POLAR DATA

The purpose of the present work is to reconsider the seasonal oscillations of brightness seen by IRAS near the ecliptic poles, through an "inverting" method which has the advantage of concentrating upon the true level of variations, i.e. the vicinity of the SP. Contrary to this approach, the crude use of brightnesses integrated along the whole los is excessively model-dependent w.r.t. remote sections of the los. In addition, the non-negligible effect due to the eccentricity of the earth's orbit will be shown.
2.1. The seasonal oscillations of brightness near the ecliptic poles

The IRAS-Explanatory Supplement (Beichman et al., 1984) gives (p. VI-10) the average brightness, \( B_0 \), and the amplitudes, \( B_1 \), in MJy sr\(^{-1}\), of the sinusoidal fits to the seasonal variations of the brightnesses \( B \) near the north ecliptic pole (NEP), in the four wavelengths of IRAS. The phase \( \phi \) is given in <days before 1983 January 1, when \( B = B_0 \) with increasing values of \( B \)>; a multiplication by 360/365.25 gives the phase \( \phi \) in degrees. The shorter two wavelengths, with lower contamination by galactic emissions, can only be used here.

<table>
<thead>
<tr>
<th>( \text{NEP} )</th>
<th>( B_0 )</th>
<th>( B_1 )</th>
<th>( \phi ) (days)</th>
<th>( \phi ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 ( \mu \text{m} )</td>
<td>13.5</td>
<td>27.6</td>
<td>23.8</td>
<td>22.3</td>
</tr>
<tr>
<td>25 ( \mu \text{m} )</td>
<td></td>
<td></td>
<td>23.5</td>
<td>22.0</td>
</tr>
</tbody>
</table>

In this section, the eccentricity of the earth's orbit is neglected. The sinusoidal variations of brightness at the NEP are completely ascribed to the alternate location of the earth "above" and "under" the SP (Fig. 2). ("Above" means that the earth is on the northern side.)

2.2. First approach for the ascending node, \( \Omega \)

Since the heliocentric ecliptic longitude of the earth on January 1 is \( \lambda_0 = 100^\circ \), and since the average value \( B_0 \) of the brightness \( B \) near the NEP was observed \( \phi \) days before, then the earth must have crossed the SP from north toward south at the ecliptic longitude of the ascending node SP/ecl.:  
\[ \Omega = \lambda_0 - \phi \]

Therefore, \( \Omega \approx 77^\circ \) (76° from 12 \( \mu \text{m} \); 78° from 25 \( \mu \text{m} \) data). (This is in full agreement with IRAS Ref. A and B.)

2.3. A retrieval of the inclination, \( i \), with low model-dependence

No physical model of the Zodiacal Cloud (w.r.t. neither its heliocentric nor its off-ecliptic, rates of decrease for the space density) is required to safely retrieve the inclination. We only have to assume the cloud to be rotationally symmetric, sufficiently extended off its SP, and moderately tilted over the ecliptic plane, so that the space density along the "polewards" los remains practically constant within the dihedron of the two planes.

If so, the increment \( \Delta B \) of brightness from its mean \( B_0 \), due to the small departure \( \Delta x = T \Delta T \) of the earth from the SP is simply proportional to \( \Delta x \) (Fig. 3) \((\Delta B > 0 \text{ when the earth is "under" the SP, we also consider then } \Delta x > 0)\). The extremal values of \( \Delta x \) over the year are \pm i (AU), those of \( \Delta B \) are \pm B_1.

The point is that the proportionality coefficient between \( \Delta B \) and \( \Delta x \) can be easily derived from the observations of IRAS in the ecliptic. This coefficient is directly provided by the derivative of the brightness vs. elongation, \( \varepsilon \), around \( \varepsilon = 90^\circ \), as already emphasized in the optical case (Dumont, 1973, 1983; Dumont and Levassuer-Regourd, 1985).

Let A and B (Fig. 4) be two positions of the earth, for which the brightnesses observed along the same los (i.e. the chord BA) would just differ by twice the amplitude seen at the poles, 2B_1. Then, the angle \( \angle B0A \) would have to be 2\( \theta \), twice the inclination (rotate Fig. 4 by 90° around OH, to successively contain the los in the ecliptic, and then the los toward the NEP).

IRAS data (Hauser et al., 1984, Table 2) does not give the brightnesses at the relevant elongations. However, the elongations 81.5° and 98.4°, practically symmetrical w.r.t. \( \varepsilon = 90^\circ \), provide another chord, wider than the previous one but unsignificantly nearer the sun. The new angle \( \angle B0A \) is 16.9°. Therefore, the proportionality \( \Delta B : \Delta x \) can be written
\[ \frac{2B_1}{2\theta} = \text{Contribution by BA} \]

which leads us to:

**Table**

<table>
<thead>
<tr>
<th>( \text{NEP} )</th>
<th>( \text{Contribution by BA} )</th>
<th>( \text{Inclination } i ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 ( \mu \text{m} )</td>
<td>16</td>
<td>1.48</td>
</tr>
<tr>
<td>25 ( \mu \text{m} )</td>
<td>23</td>
<td>1.69</td>
</tr>
</tbody>
</table>

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These results are practically insensitive to our poor knowledge of what occurs along remote sections of the two los, both in the ecliptic outside the earth's orbit, and far from the earth towards the poles.

3. CORRECTION FOR THE ECCENTRICITY OF THE EARTH'S ORBIT

This weak eccentricity (0.0167) is tempting disregard, as an apparently unessential cause of modulating the brightnesses over the year. An argument to neglect it can even be found in the fact that an elemental section of the los contributes to the brightness proportionally to its length and to its density; therefore (Fig. 3), when the earth goes away from the sun by \( \Delta R \) AU there is an increase of length for each los-section in the ratio of \((1 + \Delta R)\), and a decrease of density in a ratio of about \((1 - \Delta R)\), because of the density widely agreed to be roughly in inverse proportion to the heliocentric distance: at least a partial cancellation seems to occur.

Nevertheless, the temperature of the dust also is heliocentric-dependent. Assuming it (classically) to decrease as \( 1/r^2 \), as it would be the case in a grey-body-like cloud, the Planck term \([\exp(-h/\kappa T) - 1]^{-1}\), which rules the monochromatic emissivity, would vary by \( \pm 3.9\% \) of its average value between perihelion and aphelion, for \( T = 260 \) K at 1 AU (Levasseur-Regourd and Dumont, 1985) and for \( \lambda = 12 \) \( \mu \)m. The average 12 \( \mu \)m brightness \( B_0 \) at the poles, 13.5 M Jy sr\(^{-1}\), can therefore be expected to oscillate with about 0.5 M Jy sr\(^{-1}\) amplitude by the only effect of the eccentricity. Since this is more than 1/3 of the observed amplitude \( B_1 \sim 1.4 \) M Jy sr\(^{-1}\), clearly the eccentricity is a secondary but non-negligible cause of the seasonal oscillations observed.

Both the seasonal oscillation and its two components can be represented by rotating vectors, with the vernal point \( \gamma \) as an origin (Fig. 6). The phase of the resultant is \( \lambda_0 = \phi \); the phase of the modulation by the SP/ecl. tilt is unknown \( \Omega \); the phase of the modulation by the eccentricity is about 11\(^\circ\), i.e. the longitude of the earth on the day when its distance to the sun is 1 AU by decreasing values (about 4 October).

The amplitude of the observed resultant is \( B_1 \); let \( B_2 \) be the amplitude of the modulation by the tilt of the two planes (proportional to the unknown inclination, \( i \)). The amplitude \( E \) of the eccentricity-vector depends on the heliocentric derivatives assumed for the heliocentric correction for the space density of the dust, as shown on above example.

The most likely value for the heliocentric dependence of the temperature is \( r^{-1/1} \) rather than \( r^{-1/2} \) (Levasseur-Regourd and Dumont, 1986 : Dumont and Levasseur-Regourd, 1987). With an inverse proportionality for the radial fall of space density, the amplitude of the eccentricity-vector is \( E \sim 0.4 \) M Jy sr\(^{-1}\) in both wavelengths. As already seen it increases up to \( \sim 0.5 \) M Jy sr\(^{-1}\) for a 1/3 fall of temperature; it would reach \( \sim 0.7 \) M Jy sr\(^{-1}\) if the slightly steeper density \( r^{-1/3} \) advocated by Helios coworkers (Leinert et al., 1978) were adopted.

Even with the smoother gradients \( r^{-1/1}, r^{-1} \), the correction for eccentricity is rather important on the ascending node, which is increased by 16\(^\circ\) (12 \( \mu \)m) and by 10\(^\circ\) (25 \( \mu \)m). The inclination is only decreased by a few percent.

4. RESULTS AND DISCUSSION

The corrected parameters of the SP are

<table>
<thead>
<tr>
<th></th>
<th>12 ( \mu )m</th>
<th>25 ( \mu )m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending node, ( \Omega )</td>
<td>92(^\circ)</td>
<td>88(^\circ)</td>
</tr>
<tr>
<td>Inclination, ( i )</td>
<td>1.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Admittedly, the provisional character (w.r.t. calibration, and to residual contamination by galactic emissions) of Hauser et al.'s 1984 data induce some uncertainty upon these figures, and upon the apex of the SP, \( X \), as located on Fig. 1 by the means for the two \( \lambda \lambda' \):

\[
\begin{align*}
\Omega & \equiv 90^\circ \\
i & \equiv 1.5^\circ 
\end{align*}
\]

They seem, however, difficult to reconcile with the locations A and B which correspond to the couples \((\Omega, i)\) previously published from the same IRAS observations. On the other hand, the agreement is noteworthy with former optical results from the satellite D2A and from Tenerife ground-based data (Dumont and Levasseur-Regourd, 1978). This agreement is at least partly due to the inverting methodology, and to the correction for earth's orbit eccentricity, which were taken into account in that work.

Even various earlier determinations of the SP at the 1 AU-level (listed in 1a in Section 1 : see apex \( I \) on Fig. 1), which invoked a rough coincidence with the invariable plane of the solar system \((\Omega = 106^\circ, \ i = 1.6^\circ)\) turn out to agree better with the present result than the previous IRAS determinations do.

ACKNOWLEDGEMENTS. We are indebted to J.L. Weinberg and N.Y. Misconi for helpful information. This work was supported by "A.T.P. Planétologie" of the French INSU.
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OTHER BODIES
PROBABLE PERIODICITIES OF THE JOVIAN ATMOSPHERIC ACTIVITY

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Probable periodicities of 22.8 and 4 years have been found in the Jovian atmospheric activity measured between 1965-84.

1. Introduction

High resolution images of Jupiter obtained by the Voyager 1 and 2 flyby spacecraft on 5/3/1979 and 10/7/1979 respectively, showed remarkable details in a complex cloud system, on the horizontal structure of the Jupiter atmosphere. These layers of clouds are probably composed by ammonia crystals in the upper atmosphere, located above an ammonia hydrosulfide (NH₂SH) cloud and deeper a water ice cloud as Lewis (1969) and Gehrels (1976).

The cloud layers have been observed by ground based telescopic observations of the planet and appear as belts and zones parallel to the equatorial zone of different colours in the visible surface of Jupiter. Observational data are summarized by Peck (1958), Michaux (1967) and Gehrels (1976).

2. Measuring the activity

Focas and Banos in 1964 introduced a coefficient $R$ for measuring the activity on Jupiter which is resulting by the photometric analysis of photographic plates. This coefficient $R$ is given by the relation:

$$ R = \frac{1}{C} \int_{-45^\circ}^{+45^\circ} \left( 1 - \frac{I(\phi)}{I_C(\phi)} \right) d\phi $$

where $R$: the photometric coefficient of activity, $\phi$: the zenographical latitude, $C$: the constant reference area with limits $+45^\circ$, $I(\phi)$: the ratio between the intensities $I_B$ of a point of the polar diameter and $I_C$ of the brightest point with limits 0 to 1.

Using this coefficient of activity $R$ and photographic plates taken in yellow light with the 16" and 25" refractors of the National Observatory of Athens, Focas and Banos studied the activity on Jupiter during the period 1952-1963 (1964).

Among the different results given in that work (1964) by Focas and Banos is the decrease of the activity on Jupiter reached a minimum in 1960-1961. Combining these results with the results from previous paper of one of them (1962) they concluded that Jupiter presents a "calm" period 20-22 years.

Banos (1966) studying the activity of Jupiter for the time period 1964-66, and combining these results with previous of 1964 noticed a period of 4-5 years of the coefficient of activity. Later (1972) using 160 plates in three wave lengths taken at the New Mexico State University Observatory, for the period 1964-67 found that the photometric coefficient of activity is more intensive in the North hemisphere and presents a probable periodicity, bigger than 3 months. Focas (1971) studying the activity in Jupiter atmospheric belts between 1904-1963 using 64 negative plates at the Lowell Observatory of Flagstaff in Arizona and found a periodicity of 17-20 years.

He also noticed that Correlations with solar activity (expressed by the Wolf number), are not striking. Prinz (1971) using plates obtained with the 30 cm. cassegrain reflector of the Public Observatory in München for the period 1964-1968 studied the atmospheric activity of the planet Jupiter in the yellow light. Using graphs from the work of Focas (1971), Prinz concluded that the activity presents two long periodicities of 17 and 20 years for the maxima and 5-6 years for the minima and a small periodicity of 3 months.

Short time periodicities have been also detected in the activity of the atmosphere of Jupiter by Aksenov (1967), who noticed a three months period, which agrees with Prinz (1971) who found 92-93 days (three months) period in the green and red light and a 104 days periodicity in the blue range. Banos (1971) noticed that a periodicity bigger that 3 months can exist in the activity of Jupiter.

More recent interest studies of the atmospheric activity of Jupiter have been carried out by Petrova and Sorokina (1973), Banos-Sarris (1985) and Wilhelmenschling (1985). In (1973) Pokorny studying the evolution of the activity during the period (1964-1968) concluded that the intensity of the Jovian belts is probably affected by the occurrence of solar protons and similar events.

3. Data

In the present work we use the values of $R$ resulting from the photometric analysis of plates taken by Banos mainly during the period 1962-1984. The values of $R$ are calculating with the method Focas-Banos (1964, 1971) and the plates used are taken in the National Observatory of Athens with the 16", 25" refractors and the 48" telescope.

For the period 1904-1962 we use the results published by Focas (1971).
In figure 1 we give the evolution of the activity of the atmosphere of Jupiter for the time period 1956-1985, connected with other results obtained by Banos (1971) Banos-Focas (1964) for the latitude zone $+45^\circ$, and Sarris (1975).

4. Mathematical analysis of the coefficient of activity.

We have used the method of analysis in trigonometric series in order to represent analytically time variation of the coefficient of activity $R(t)$.

Mean values, computed by the moving averages method of the measured coefficient of activity are given in the curve (a) of figure 2.

The analytical expression of $R(t)$ can be given by the following relation.

$$R_1(t) = 0,240 - 0,025 \sin \frac{2\pi}{22} (T-1914) - 0,020 \sin \frac{2\pi}{22} (T-1937)$$

1914-1938

$$-0,040 \sin \frac{2\pi}{22} (T-1964)$$

1943-1955 + 0,040

$$-0,040 \sin \frac{2\pi}{22} (T-1979)$$

1964-1973 + 0,050

which gives the time period of 20 years while the 8 and 4 years period is given by:

$$R_0(t) = 0,30 \sin \frac{2\pi}{8} (T-1914) - 0,010 \sin \frac{2\pi}{8} (T-1925) -$$

$$-0,40 \sin \frac{2\pi}{8} (T-1938) + 0,040 \sin \frac{2\pi}{8} (T-1964) +$$

$$+0,040 \sin \frac{2\pi}{8} (T-1969) - 0,50 \sin \frac{2\pi}{8} (T-1974) -$$

$$-0,016 \sin \frac{2\pi}{4} (T-1955)$$

1928-1932 + 0,040

1964-1973 + 0,050

1980-1986 + 0,060

In Figure 2, curve (a) gives the periodical term of 22 years while, curve (b) gives the periodical terms of 4 and 8 years.

In the same figure curve (c) represents differences of the computed values $R(t)_{comp}$ from the measured values given by curve a in the same figure.

$$R_0(t)_{comp} = R(t)_{obs} - R(t)_{comp}$$

periodicity of $R_0(t)$, which is of 4 years with an accuracy of 95%. The time intervals and the amplitude of this periodicity are given by the analytical expression.

$$R_0(t) = b_n \sin \frac{2\pi}{8} (T-1914) + c_n \sin \frac{2\pi}{4} (T-1964)$$

where the values of $b_n$, $c_n$, $T$ are given in Table 1.

$$\begin{align*}
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\text{T} & \quad \text{A} \text{N} \text{S} \text{E} \\
\end{align*}$$

After the above we now computed the analytical expression of $R(t)$.

The computed values by this relation are compared to the observed ones in Table 2.

The standard deviation, between the observed and computed values is:

$$\sigma = \pm 0,0043$$

with an accuracy $A = (1- \frac{\delta}{0,240})100\% = 98,1\%$

The above analysis has 31 parameters and 38 degrees of freedom.

Results and Discussions

The following periods have been found for the coefficient of atmospheric activity of Jupiter.

(1) 22 years period for the time interval 1914-86.

(2) Small periodicities of 4 years and 8 years.

The periodicity of 20-22 years has been suggested by Focas-Banos (1964). The 22 years period, could be interpreted as a result of the solar activity, Balasubrah-
husanuyan and Vernkatesan (1970), and Krisky
et al (1972) show that the variations of solar
activity caused by the fluctuating occurrence
of proton events on the Sun can also be obser-
ved on the planet Jupiter at 5A.U distance.
Pokorny (1972), using superposition method,
studied relationship between Jupiter's pho-
tometric coefficient R and proton events for
the period 1904-1968, and concluded that the
analysis of the coefficient R yielded a two-
maximum relationship over the 11 year cycle.

In fact recently Voyager I and 2 spacecrafts
detected plasma waves beyond 12 A.U. during
the time period 1982-1984. (Lanzerotti, et al
1985). These plasma waves could be associ-
ated with turbulence expected at the heliopause.
Energetic protons have been also measured by
Voyager I about the same time intervals. (Lan-
zerotti et al 1985). Then it is probable that
solar wind streamers, active the Jupiter mag-
netosphere, which interacts with the global
years which we have found in the index of the
atmospheric activity of Jupiter.

Solar wind streamers have as sources coro-
nal holes or solar flares and their number
have been recently studied by Xanthakis et
al (1986) who found for the time period 1969-
1984 11 years and 7 year periodicities for
the solar wind streamers, which have flares
as sources and 14 years 2 and 1 year periods
for the solar wind streamers provided by cor-
nal holes. Then it is probable that the
22 years period (Hale period) for the number
of sunspots Rg and for the flares, modulates
the solar wind and interacts with the global
circulation of the winds, while the shorter
time periodicities interact with the clouds
morphology of Jupiter.

From figure 1 in which we give the evolu-
cation of the coefficient of activity R for
the period 1904-1984 comparing it with the
Wolf number we can notice that an anticor-

![Graph](image_url)

Fig.2. Curve (a) gives the periodical term of 22 years.
Curve (b) gives the periodical terms of 4 and 8 years.
Curve (c) represents the differences of the computed values
R(t),comp from the measured values given by curve a.
maxima of Wolf number for the 20th and 21st solar cycles respectively. The second maximum of the 20th cycle appears in 1972 and coincides with the second maximum of the green line intensity of the corona. (Xanthakis 1934) which is well correlated with the number of proton flares. A second minimum appeared in 1982 which corresponds also to the second maximum of the green line. (Xanthakis 1934) It seems therefore that the suggestion of Pokorny (1973) in which proton flares interact with the activity of Jupiter is verified for the 20th and 21st solar cycles. Banos and Basu (1976) have also studied probable relations between Jupiter's decametric radio emission and its activity. They found significant correlation between the peculiar activity in the equatorial area of the planet and the Jovian decametric radiation at 18.0, 22.2, 27.6 MHz.

According our opinion relationships ought to exist between solar wind streamers of solar flares or solar coronal holes, and the magnetosphere of Jupiter, and an interaction with the chromospheres of its clouds system, with probable variations of the coefficient of activity R. However internal sources of Jupiter radiation, as the decametric radiations, could also effect the Jovian activity.

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### TABLE II

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<tr>
<th>Years</th>
<th>$R(t)$ Comp.</th>
<th>$R(t)$ Obs.</th>
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<td>1916</td>
<td>0.240</td>
<td>0.230</td>
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<td>1917</td>
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</tr>
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<td>1930</td>
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<td>1931</td>
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<td>1933</td>
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<th>$R(t)$ Obs.</th>
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<td>1980</td>
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A REFERENCE MODEL FOR THE ATMOSPHERE OF TITAN  
B. Petropoulos, A.A. Georgakilas  
Research Center for Astronomy and Applied Mathematics,  
Academy of Athens, 14 Anagnostopoulou Street- Athens (136) Greece

We have computed the following physical parameters for the atmosphere of Titan, using Voyager's measurements: 1) Temperature, 2) Pressure, 3) Density, 4) Speed of sound, 5) Density scale, 6) Number Density, 7) Mean free path, 8) Viscosity, 9) Pressure scale, 10) Mean particle velocity, 11) Mean collisional frequency, 12) Columnar mass

I. INTRODUCTION

Titan has been observed by ground based telescoping observations (Kuiper et al, 1952) and by the recent missions of Voyager spacecrafts. The satellite of Saturn appears from Voyager 1 cameras (1980) as surrounded by a dens uniform haze. Its atmosphere consists mainly from N2 and it is filled with aerosols.

II. BASIC ASTRONOMICAL DATA

Properties of Titan are given in Table I (Allison et al, 1986). The mean solar distance R (or semimajor axis) and the orbital eccentricity are specified as the (rounded) values for the osculating elements tabulated in the Astronomical Almanac (1986). Distances are given in Astronomical units with 1 AU = 1.49598X10^11 Km. The osculating mean distance change by as much as a few tenths of a percent. Its eccentricity mostly change, no more than ten percent of its tabulated value. The orbital period is taken from Allen's Astrophysical Quantities (1973). The Southern solstice dates are compiled or extrapolated from data in Allen (1973) and the Astronomical Almanac. As also the obliquity which is the inclination of a planet's equator to its orbital plane. The sidereal rotation period is taken to be the same as its orbital period about Saturn (as reported by Davies et al 1980) assuming that its rotation is tidally locked to the planet.

Titan's equatorial radius has been derived from Voyager radio occultation measurements assuming that the satellite is spherical (Lindal et al, 1983). The indicated altitude of the main haze level on Titan corresponds to the elevation of its optical limb as measured by Voyager's imaging (Smith et al, 1981).

Bond albedo is derived from the effective temperature, estimated by Lindel et al (1983) assuming that the internal heat source is negligible.

TABLE I

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Surface radius r_s</td>
<td>2575 Km</td>
</tr>
<tr>
<td>Mass M</td>
<td>1346X10^26 gr=0.022XEarth</td>
</tr>
<tr>
<td>Mean &lt;g&gt;</td>
<td>135.4±0.1 cm/sec^2</td>
</tr>
<tr>
<td>GM</td>
<td>8.976X10^10 cm^3/s^-2</td>
</tr>
<tr>
<td>Rock:ice ratio(by mass)</td>
<td>52:48</td>
</tr>
<tr>
<td>Distance from Saturn</td>
<td>1.226X10^6 km=20 R_s</td>
</tr>
<tr>
<td>Mean Solar distance</td>
<td>9.546 A.U.</td>
</tr>
<tr>
<td>Orbit period around Saturn</td>
<td>15.945 days</td>
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<tr>
<td>Orbit period around Sun</td>
<td>30 years</td>
</tr>
<tr>
<td>Axial inclination</td>
<td>26.7°</td>
</tr>
<tr>
<td>Bond albedo</td>
<td>0.22</td>
</tr>
<tr>
<td>Solar flux</td>
<td>1.1% Earth</td>
</tr>
<tr>
<td>Southern Summer Solstice</td>
<td>2002.5</td>
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<tr>
<td>Effective emission temperature</td>
<td>85 K</td>
</tr>
<tr>
<td>Effective emission pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Dry adiabatic lapse rate</td>
<td>1.3 K K m^-1</td>
</tr>
<tr>
<td>Static Stability</td>
<td>0.7 K K m^-1</td>
</tr>
<tr>
<td>Scale height</td>
<td>20 Km</td>
</tr>
<tr>
<td>Emission level Pe</td>
<td>7.5</td>
</tr>
<tr>
<td>Surface (or H2O) Ps</td>
<td>8.4</td>
</tr>
<tr>
<td>Meridional thermal gradient</td>
<td>-1 K 10^2 Km</td>
</tr>
<tr>
<td>Radiative time constant Pe</td>
<td>2X10^6 sec</td>
</tr>
<tr>
<td></td>
<td>3X10^6 sec</td>
</tr>
</tbody>
</table>

FIGURE 1. Temperature versus altitude.

FIGURE 2. Pressure versus altitude.
III. CHEMICAL COMPOSITION

Atmospheric composition of Titan below 0.1 bar is given in Table II. (Sagan and Thomson, 1984).

All values are derived directly or indirectly from Voyager data. Hydrocarbons and nitriles are formed on the stratosphere from dissociation of CH$_4$ and N$_2$ (Gautier et al.).

A crucial question in Titan concerns possible implications of the discovery of HCN, HC$_3$N and C$_2$H$_2$ nitriles in the upper atmosphere. HCN is a key intermediate in the synthesis of amino acids. Laboratory experiments have demonstrated that once HCN has been produced more and more complex nitriles are easily formed. Sagan and Thomson (1984) have given, on the basis of laboratory experiments of irradiations of simulated Titanian atmospheres an impressive list of complex organic solids which could have been formed in Titan.

<table>
<thead>
<tr>
<th>Name</th>
<th>Abundance</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>~85-77%</td>
<td>4,8,9</td>
</tr>
<tr>
<td>Argon</td>
<td>~12-17%</td>
<td>4,9</td>
</tr>
<tr>
<td>Methane</td>
<td>~3-6%</td>
<td>1,4,6,7</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.1-0.4%</td>
<td>4,6</td>
</tr>
<tr>
<td>Ethane</td>
<td>20 ppm</td>
<td>1</td>
</tr>
<tr>
<td>Propane</td>
<td>20-50ppm</td>
<td>2,10</td>
</tr>
<tr>
<td>Ethyne</td>
<td>2 ppm</td>
<td>1</td>
</tr>
<tr>
<td>Ethene</td>
<td>0.4 ppm</td>
<td>1</td>
</tr>
<tr>
<td>Methanenitrile</td>
<td>(Hydrogencyanide) 0.2 ppm</td>
<td>1</td>
</tr>
<tr>
<td>Bytadiyne</td>
<td>0.03 ppm</td>
<td>3</td>
</tr>
<tr>
<td>(diacetylene)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propyne</td>
<td>0.03 ppm</td>
<td>2</td>
</tr>
<tr>
<td>Propynenitrile</td>
<td>(methylacetylene) 0.03 ppm</td>
<td>2</td>
</tr>
<tr>
<td>Cyanogen</td>
<td>0.1-0.01ppm</td>
<td>3</td>
</tr>
<tr>
<td>Ethanedinitrile</td>
<td>(cyanogen) 0.1-0.01ppm</td>
<td>3</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.01 ppm</td>
<td>5</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>60 ppm</td>
<td>11</td>
</tr>
</tbody>
</table>
FIGURE 7. Mean free path versus altitude

FIGURE 8. Viscosity versus altitude

FIGURE 9. Pressure scale versus altitude

FIGURE 10. Mean particle velocity versus altitude

FIGURE 11. Collisional frequency versus altitude

FIGURE 12. Columnar mass versus altitude

IV. TEMPERATURE PROFILES

Temperature profiles of Titan's atmosphere measured by Voyager with two methods:
1) By radioculation at 7°N, 258°E and at 80°S, 76°E (Lindal et al., 1983)
2) By infrared spectroscopy at 7°N and at 80°N (Hanel et al., 1981).

A tropopause lapse which is subadiabatic at all levels appear adiabatic for the lowest three to four km that applies that the vertical thermal structure is windly convert by radiative process and that convection is predominant at the lower boundary of the atmosphere.

Temperature profiles measured by radioculation data are given in figure 1. (Lindal et al., 1983) There is a little difference between measurements obtained in North hemisphere from that obtained in South hemisphere at altitudes above 100 km.

V. INPUT DATA AND RESULTS

In order to compute the physical parameters we resolved the hydrostatic equation by assuming that:
The atmospheric gas behaves as a real gas and follows the equation of state (Lindal et al., 1983)

\[ p = \rho m \frac{R}{T/Fc} \]  

Where, \( p \) is the pressure, \( \rho \) is the density, \( m \) is the mean molecular weight, \( T \) is the temperature, \( R \) is the universal gas constant and for N2 Fc is given by the formula:

\[ Fc = 1 + \frac{A_0}{Ti} \]  

where, for SI-units, the constants A and B are:  
A = 0.0563, B = 2.75  
(Lindal et al., 1983) Ti is the ideal gas temperature.

The following input data have been used for the computations:
1) The radius of the satellite measured by Voyager, R=2575 km (Lindal et al., 1983)
2) The chemical composition of the atmosphere N2: 100% (Lindal et al., 1983)
3) The mean molecular weight computed by taken into account the above chemical composition and considered to be constant from 0 km to 200 km, \( \bar{m} = 28.02 \)
4) The pressure and temperature at zero altitude a) Po = 1497.59 mb and To = 93.9 K for radioculation experiment at 80° South and 76° East longitude in the morning atmosphere.
5) The two different temperature profiles versus altitude measured by radioculation which we mention in section V. (Lindal et al., 1983). The physical parameters which we have computed are: 1) Temperature (fig.1), 2) Pressure (fig.2), 3) Density (fig.3), 4) Speed of sound (fig.4), 5) Density scale (fig.5), 6) Number density (fig.6), 7) Mean free path (fig.7), 8) Viscosity (fig.8), 9) Pressure scale (fig.9), 10) Mean particle velocity scale (fig.10) 11) Mean collisional frequency (fig.11), 12) Columnar mass (fig.12) (Dashed lines represents the computed values for 80° latitude and 258° East longitude, Solid lines represents computed values for 80° South latitude and 76° East longitude).

V. CONCLUSIONS

We give a reference model for the atmosphere of Titan, as a first attempt in order to study this atmosphere. Lumine (1983) suggest that the surface of Titan is covered by an ocean of 75% CH4 and 25% N2 and the vapour of these components form clouds of CH4 crystals at altitudes 20-40 km.

If we compare the computed pressures and temperatures with the liquifying temperatures of CH4 which is probably abundant in 3-6% in the atmosphere of Titan, we can derive that probably the surface of Titan is covered with oceans of CH4 and other hydrocarbons. The computed physical parameters can be used in laboratory experiments in order to study the evolution and the meteorology of Titan's atmosphere.

REFERENCES


V. CONCLUSIONS

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