COMMISSION 15 : PHYSICAL STUDY OF COMETS, MINOR PLANETS AND METEORITES
(L'ÉTUDE PHYSIQUE DES COMÈTES, DES PETITES PLANÈTES ET DES MÉTÉORITES)

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1 Introduction

The period covered by this report, 1984 July to 1987 June, was of extraordinary importance for the progress of cometary physics. For the first time in the history, special space probes were launched to comets. Vega 1, Vega 2 and Giotto encountered P/Halley, providing us with the first close-up pictures of a cometary nucleus, its surface features, and with the first in situ measurements of the matter escaping from it. ICE, Suisei and Sakigake carried out measurements relevant to P/Giacobini-Zinner and P/Halley in interplanetary space. Unprecedented worldwide campaigns of ground-based observations, with the participation of about 1000 professional and 2000 amateur astronomers, were coordinated in 8 sections of the International Halley Watch. Additional measurements were made from artificial satellites, sounding rockets, and high-flying airplanes. The wealth of data collected in this way, to a major extent thanks to an excellent international cooperation, represents a milestone in cometary astronomy. Another important step was the progress in processing the extensive 1983 IRAS observations of minor planets and comets, including the discovery of asteroid dust bands and cometary dust trails.

There were so many international meetings dealing at least partially with the subject area of our Commission, that it is only possible to quote some of them : Asteroid Missions (Graz 1984), Halley Up-Date (Graz 1984), Properties and Interactions of Interplanetary Dust (Marseille 1984), Asteroids, Comets, Meteors II (Uppsala 1985), The Evolution of the Small Bodies of the Solar System (Varenna 1985), Catastrophic Disruption of Asteroids and Satellites (Pisa 1985), Field, Particle and Wave Experiments on Cometary Missions (Graz 1985), Astrochemistry (Goa 1985), Comet Halley (New Delhi 1985), Comets Halley and Giacobini-Zinner (Toulouse 1986), The Multi-Comet Mission (Greenbelt 1986), The Comet Nucleus Sample Return Mission (Canterbury 1986), Exploration of Halley's Comet (Heidelberg 1986), Meteorites and the Early Solar System (Tucson 1987), The Diversity and Similarity of Comets (Brussels 1987), Physical Interpretation of Solar/Interplanetary and Cometary Intervals (Huntsville 1987). More information about the programs, dates, organizers, sponsors, and proceedings of these meetings can be found in the IAU Information Bulletins or in the Astronomy and Astrophysics Abstracts. The Halley meeting at Heidelberg, with 500 participants from 30 different countries and 370 papers presented, was the largest meeting on interplanetary objects in the history.

From among the numerous books, monographs, and extensive review papers, the following may be quoted : The Mystery of Comets (Whipple 1985), Asteroids (Simonenko 1985), Propriétés Physiques et Chimiques des Comètes (Arpigny 1985), The Physics of Comets (Mendis, Houpis and Marconi 1985), Cometary Dynamics (Weissman 1985), Long-term Evolution of Short-period Comets (Carusi, Kresák, Perozzi and Valsecchi 1985), Kometen (Möhlmann, Sauer and Wäsch 1986), Physics of Comets (Krishna Swamy 1986), The Origin of Comets (Bailey, Clube and Napier 1986), IRAS Asteroid and Comet Survey (ed Matson 1986), Catalogue of Short-period Comets (Belyaev, Kresák, Pittich and Pushkarev 1986), Cometary Nuclei

(Shulman 1987), Physics of Radiation of Planetary and Cometary Atmospheres (Krasnopolsky 1987), Asteroid Photometric Catalog (Lagerkvist, Barucci, Capria, Fulchignoni, Guerriero, Perozzi and Zappalà 1987). Information about the publishers or publishing journals can be found again in the Astronomy and Astrophysics Abstracts. For new editions of the catalogues of orbits, designations, absolute magnitudes and ephemerides of minor planets and comets see the reports of Commissions 6 and 20.

In spite of over 700 references included, the present report is obviously incomplete. This refers, in particular, to the broad and interdisciplinary meteorite research, from which only some results relevant to the origin of the solar system and evolutionary links to other types of objects were selected. The boom in the space exploration of comets has also made it necessary to reduce the information on asteroids. The references are given in a very succinct form, as explained by the key at the end of the report.

The preparation of this report would have been impossible without a kind cooperation of a number of colleagues. Drafts of the chapters on comets were written by B D Donn (Cometary Nuclei), M F A'Hearn (Cometary Gases), W H Ip (Cometary Plasma), E Grün and A C Levasseur-Regourd (Cometary Dust), and H Rickman (Origin and Evolution of Comets). A review of the cometary research in the USSR was provided by O V Dobrovolsky, and incorporated into the relevant chapters by C Arpigny, who also made a number of other additions and changes to avoid duplicities. The chapter on Minor Planets was prepared by A W Harris with the assistance of P Farinella and D F Lupishko. The chapter on Spacecraft Missions to Comets and Asteroids was written by J Rahe. The chapter on Meteorites was prepared by J T Wasson with the assistance of D Brownlee, J Gooding, R Grieve, R Hewins, I Hutcheon, G Kallemeyn, A S Kornacki, F Kyte, D Malvin, A E Rubin, E Scott, and P Warren. The final arrangement of the report, with a number of minor changes, was done by the Commission President, who takes the responsibility for any omissions and errors, and acknowledges with sincere thanks the kind help of all the above mentioned co-authors, especially the great share of Claude Arpigny.

2 Cometary Nuclei

Several major developments in research on the cometary nuclei have occured in the interval covered by this report. Foremost, was the Comet Halley encounter during which three space probes actually observed the nucleus. A second was the increasing acceptance of the concept that the nucleus is a non-uniform, low density aggregate of cometesimals. This picture received considerable support from the encounter images. A third is the very non-uniform surface activity of the nucleus, as demonstrated by Sekanina and Larson over several years and directly seen during the encounter imaging. These two, now generally accepted nuclear characteristics, greatly complicate theoretical analyses of the thermal behaviour and evolution of the nucleus, as the greatly simplifying assumptions of spherical symmetry and uniform angular and radial properties can no longer be made.

COMET P/HALLEY

Publications dealing with the nucleus of P/Halley during its 1986 apparition are very extensive as a result of two Vegas and the Giotto spacecraft encounters. The primary results were : (1) detection of a single nucleus; (2) direct measure of size and shape - irregular elongated nucleus about 16 km long with width 7.5 to 8 km. The surface shows features to the limit of resolution, about 50 m for the Giotto camera; (3) the surface is very non-uniform with respect to ejection of matter, with only about 20 percent being active during the encounter; (4) combination of the dimensions of the nucleus with its visual magnitude at very large heliocentric distances (> 6 AU) leads to a very low geometric albedo of approximately 4 percent; the nuclear surface is quite warm (≥ 300 K), which suggests the presence of an insulating dust layer on top of the volatile material (Sagdeev et al, Nat 321, 262; ESA 250/2, 317; Keller et al, Nat 321, 320; ESA 250/2, 347; Möhlmann et al, Bertaux and Abergel, Reitsema et al, and Wilhelm et al, ESA 250/2, 339, 341, 347, and 367; Combes et al, Nat 321, 266; Emerich et al, ESA 250/2, 381).

CHARACTERISTICS OF NUCLEUS AND NUCLEAR MODELS

Whipple (ESA 250/2, 281; NASI 156, 343), Sekanina (ASR 5, 307), and Wood (ESA 249, 123) have reviewed various aspects of nuclear models, characteristics and behaviour. Recent models emphasizing the nucleus as a compact collection of aggregates have been presented by Weissman (Nat 320, 242), and by Gombosi and Houpis (Nat 324, 43). Donn and Hughes (ESA 250/2, 523) starting with random accretion of grains and clusters have proposed a low-density porous, somewhat compressed, fractal-like structure. Greenberg (ACM II, 221) also proposed a low-density comet model. Rickman (ESA 249, 195) reported a determination of masses and densities of P/Halley and P/Kopff, and obtained densities of 0.1-0.2 g cm^{-3}.

ORIGIN

The comet formation environment has been examined by Yamamoto on the basis of equilibrium vaporization of interstellar molecules (AA 142, 31; NASI 156, 205). Clube and Napier (Ic 62, 384) and Napier and Humphries (MN 221, 105) treated comet formation in molecular clouds. A review of theories of comet origin by Bailey appeared in Vistas in Astronomy (29, 53). Implications for planet formation were discussed by Weissman (PP II, 895). The origin and dissolution was examined by Oort (Obs 106, 186). Dynamics of accreting cometesimals in the region of the outer planets was reviewed by Greenberg et al (IAUC 83, 3).

NUCLEAR ROTATION AND PRECESSION

Rotation of nuclei was discussed by Wallis (PTRS 313/A, 165). The rotational state of the nucleus of P/Halley appeared to be complex, different lines of evidence indicating periodicities of about 2.2 and 7.4 days. For the current various interpretations see Sekanina (Nat 325, 326); Julian (Nat 326, 57); Smith et al (Nat 326, 573); Wilhelm (Nat 327, 27), and references therein. For P/Arend-Rigaux, Jewitt and Meech (Ic 64, 329) derived a period of 9.58 or 6.78 hours. Precession of the nucleus and consequences for cometary evolution for several comets have been studied by Sekanina (AJ 89, 1573; AJ 90, 877 and 1370).

THERMAL MODELS AND EVOLUTION

An active area of cometary research has been modelling of the thermal behaviour and evolution of the nucleus, particularly mantle formation. Numerical simulations were carried out by Herman and Podolak (Ic 61, 252 and 267); Weissman and Kieffer (JGR 89, C235; ASR 4, 221); Weissman (ESA 250/3, 517); McKay et al (JGR 90, 1231; Ic 66, 625); Fanale and Salvail (Ic 60, 476); Ip and Rickman (ESA 249, 181); and Houpis et al (ApJ 295, 654). Kührt et al have treated thermal stresses in cometary ices (Ic 60, 512; Ic 61, 124; ASR 4, 225; ASR 5, 105; ESA 250/2, 385). The evolution of cometary ice structure was investigated by Smoluchowski et al (EMP 30, 281; NASI 156, 397) and by Klinger (NASI 156, 407). Observations of P/Kopff were interpreted by Cochran (AJ 91, 674) as evidence for a mantle development. Dust mantle formation and evolution were modelled by Rickman and Fernández (ESA 249, 185). Theoretical work of Shulman, including a theory of the dust mantle formation and evolution, and a purely analytical approach to the thermal regime problem, has been summarized in his monograph (Cometary Nuclei, Moscow 1987). The latter problem has also been treated numerically for a variety of models by Marov et al (AV 21, 47), and by Ibadinov and Aliev (KM 39, 3). The progressive dust layer growth was suggested to be a typical phenomenon of comets, as indicated by their secular brightness decrease and its dependence on perihelion distance (Dobrovolsky et al, ESA 250/2, 389). The reactive force acting on P/Halley's nucleus was evaluated by Kolesnichenko and Skorov (KIAM 84, 61).

LABORATORY STUDIES

Laboratory modelling of surface matrices continued at Leningrad and at Dushanbe. Among the items treated there were : formation of polymers under UV action on water ice with admixtures of nitriles or aminoacids (Lisunkova and Kajmakov, KTs 364 and 366); conditions of amorphous or crystalline grain formation, and structural elements of the grains (Lisunkova, KTs 366); mechanical and thermal properties of organic dust matrices (Ibadinov et al, DANT 28, 21; Ibadinov and Rakhmonov, KTs 360) - main results: densities 0.01 to 0.05 g cm^{-3}, compressive strength 0.05 to 0.5 kg cm^{-2}, thermal conductivity 10^{-1} W m^{-1} K^{-1}; creation of negative ions and clusters of both signs under simulated solar wind action (Hashimov and Shoyekubov, ESA 250/3, 189); sublimation of solid H_2O with admixture of CO_2 proceeding in the form of microbursts with ejection of icy grains up to millimeter-sized ones (Ibadinov and Aliev, KM 36, 35); these observations are in line with Kajmakov's thermobarodestruction concept (KTs 280), and with ideas by Kührt (Ic 60, 512). An experimental study of low-density residues was carried out by Saunders et al (Ic 66, 94).

3 Cometary Gases

PHOTOPROCESSES

The fluorescent emission of OD was modelled by A'Hearn et al (ApJ 297, 826), that of CO^+ by Magnani and A'Hearn (ApJ 302, 477), that of CN, including isotopic variants, by Zucconi and Festou (AA 150, 180; AA 158, 382), that of CO, including collisions but only for the infrared bands, by Chin and Weaver (ApJ 285, 858), and that of H_2O^+, vibrational structure only, by Lutz (ApJ 315 L147). Krishna Swamy calculated profiles of the B-X bands of CO^+ (EMP 34, 281) and of some Swan bands of C_2 (MN 224, 537), the latter for isotopic variants. Photodissociation lifetimes, including the Swings effect, were calculated for OH and OD by Van Dishoek and Dalgarno (Ic 59, 305) and for NH by Singh and Gruenwald (AA 178, 277). De Almeida and Singh (EMP 36, 117) calculated the photodissociation lifetimes of S_2. Pehler and Kegel (AA 155, L13) showed that formation of OH in excited states should affect the observed relative populations by no more than a few percent, whereas Bertaux (AA 160, L7) used relative brightnesses of OH on and off the nucleus to argue for the direct formation of OH in the excited A state. Crovisier (AJ 90, 670) improved his earlier models for the excitation of radio lines of H_2O, CO, HCN, and NH_3.

HYDRODYNAMIC AND PHOTO-CHEMICAL MODELS

Marconi and Mendis (ApJ 287, 445; EMP 36, 249) improved their earlier hydrodynamic models of the coma by including the effects of heating by the diffuse radiation scattered and thermally emitted by the dust in the coma. Gombosi et al (ApJ 293, 328; ApJ 311, 491) have also considered the hydrodynamic flow of a dusty gas and applied it particularly to modelling cometary outbursts. Kitamura modelled axisymmetric jets with and without dust (Ic 66, 241). Yamamoto and Ashihara (AA 152, L17) argued that the water vapor in the inner coma should recondense into icy grains. Ip (ApJ 300, 456) then calculated the heating effect on the gases of the coma due to this recondensation. Beard et al (ApJ 295, 668) argued that the pressure scale length on the sunward side should be shorter than the decay scale length for CN and C_2 and should therefore control the physical processes.

A numerical stochastic modelling of the photochemistry of cometary atmospheres was presented by Marov and Shematovich (KIAM 85, 176). On this basis the same authors gave a numerical investigation of the photochemistry of an H_2O dominated cometary atmosphere (KIAM 87, 90). Physico-chemical processes in the coma were treated in the frame of the multiphase and multicomponent radiating mixture theory with allowance for chemical reactions and heat and mass transfer (Kolesnichenko and Marov, KIAM 85, 61).

OBSERVATIONAL MODELLING

Haser model scale lengths were determined by Hu et al (ChAA 9, 86) and by Combi and Delsemme (ApJ 308, 472) using old data for CN and C_2, and by Cochran (AJ 90, 2609) using new data. There is not yet good agreement among different investigators on these scale lengths. Cochran (ApJ 289, 388) used her data to show that more complicated models with non-equilibrium photochemistry were required to fit C_2 profiles. Bockelee-Morvan and Crovisier (AA 151, 90) considered a variety of possible parents for CN and evaluated lifetimes an excitation conditions.

A generalized Haser method with account for solar light pressure and scale lengths of both parent and daughter molecules was developed and used to explain the asymmetry of coma isophotes and to improve scale lengths of molecules (Dranevich and Matveev, KM 37, 3). A method to distinguish between compact and extended sources of molecules in cometary atmospheres was developed and applied to prove the existence of extended sources (Dranevich, KTs 340). The possible role of charge transfer between N_2 and solar He^+ to excite the Meinel bands of N_2^+ was discussed by Cherednichenko (KTs 340).

Gérard (AA 146, 1) has interpreted the frequency shifts of the radio lines of OH observed in comet Austin 1982 VI as being due to Zeeman shifts which require a field of 50 gamma. Fink and Johnson (AJ 89, 1565) derived spatial profiles of [OI] emission in P/Tuttle and P/Stephan-Oterma, which agree well with models based on dissociation of water. Absolutely calibrated spectra of P/Tuttle, P/Stephan-Oterma, P/Brooks 2, and 1982 I Bowell were presented by Johnson et al (Ic 60, 351). Ip et al (ApJ 293, 609) then deduced abundances of H_2O^+ and interpreted them in terms of photoionization of H_2O. Spectrophotometry at many points in the coma of P/Stephan-Oterma was presented by Cochran and Barker (Ic 62, 72). Cochran (Ic 62, 82) then modelled these data using a variety of chemical and photochemical reactions. Cochran (AJ 92, 231) used data on many comets from three observing teams to determine the typical relative abundances of C_2, CN, and C_3. Festou (ASR 4, 165) considered the various carbonic species in a variety of comets and concluded that there are large variations in the C/OH ratio from comet to comet. He also restudied the relationship between production of OH and visual magnitude (ACM II, 299). Feldman (ACM II, 263) reviewed the observations of CO in comets. Butterworth et al (ACM II, 269) reported new emission bands of CS. Azulay and Festou (ACM II, 273) showed that optical depth effects were important for S and argued that the abundance of S could not be explained by CS_2 and CS. Cochran (AJ 91, 646) reported a major asymmetry about perihelion in her spectrophotometry of P/Kopff and suggested an interpretation in terms of mantle development.

SPECIFIC COMETS

Spectral differences between different parts of the split comet West 1976 VI, and their temporal changes were examined by Rosenbush (Ic 66, 230).

The remarkably close approach to Earth by comet IRAS-Araki-Alcock 1983 VII in May 1983 led to many unique observations, the results of which continued to appear. Cosmovici and Ortolani (Nat 310, 122) reported the existence of hitherto unobserved HCO and H_2S^+, as well as the possible presence of several other species. Temporal variations during an outburst were discussed by Feldman et al (ApJ 282, 799) in terms of a rotating model of the nucleus. They point out the value of S_2 as a tracer of activity of the nucleus. A'Hearn and Feldman (NASI 156, 487) argued that the presence of S_2 implied that the cometary ices had never been significantly heated. Bockelée-Morvan et al (AA 141, 411) and Irvine et al (Ic 60, 215) presented upper limits for HCN and showed that these were lower than the observed production of CN. Oliversen et al (Ic 63, 339) observed a "hole" in the C_2 at the center of the comet. Jockers et al interpreted the anisotropy of the coma in terms of a nuclear model with chemical differentiation (ACM II, 331). Jackson et al (ApJ 304, 515) used the spatial profiles of CS with lifetimes measured in the laboratory to infer that CS_2 must be its parent. Lutz and Wagner reported remarkable, rapid variations in the abundances of C_2, C_3, CN, and CH on May 9 (ApJ 308, 993).

Comet P/Crommelin was observed by many. Festou et al (AA 152, 170) showed that the UV spectrum was similar to that of most comets except that C was weak. Bockelée-Morvan et al (AJ 90, 2586) observed the radio lines of OH. Russell et al (MN 217, 651) obtained C_2 production rates. Wallis and Carey (MN 217, 673) determined that H was more abundant than could be explained by the observed OH. An archive of all known observations was published by Sekanina and Aronsson (JPL Publ 86-2).

Comet P/Encke was shown by Feldman et al (Ic 60, 455) to exhibit normal relative abundances but with highly anisotropic ejection. A'Hearn et al (Ic 64, 1) showed that the optical asymmetry about perihelion does not reflect the total outgassing as measured by OH. Djorgovski and Spinrad (AJ 90, 869) presented surface photometry and suggested that the shape of the isophotes was due to radiation pressure on C_2 and CN.

Comet P/Giacobini-Zinner was the first comet to be visited by spacecraft, an event which led to numerous firsts although most of these were discoveries about the plasma properties rather than the gas. The known atypical composition (C_2 and C_3 depleted) was documented by Cochran (AJ 92, 239). Ogilvie et al (Sci 232, 374) reported the detection of the long predicted H_3O^+ as well as an ion mass 23 or 24, the identity of which is still in some dispute. Na^+, Mg^+, C_2^+, and others have all been suggested in papers by Geiss et al (AA 166, L1) and by Ip and Axford (Nat 321, 682). Schleicher et al (ESA 263, 31) showed that the inversion of the lambda-doublet of OH was quenched in the inner coma as predicted by radio observers. The spatial profile of H_2O^+ was obtained by Strauss et al (GRL 13, 389) and compared with the plasma profile measured by ICE, finding good agreement (see also AJ 92, 474). They estimated an H_2O^+ abundance 1/4 that of electrons. Lyman-alpha monitoring with Pioneer Venus was discussed by Combi et al and compared with models to derive production rates (GRL 13, 385). Radio emission by OH was studied by Norris et al (PASA 6, 180). Rees et al (ASR 5, 267) monitored various neutral and ionic species for several weeks around the encounter while Perez-de-Tejada et al (ASR 5, 293) obtained spectra at the time of the encounter showing the comet steady. McFadden et al (Ic 69, 329) monitored the UV emissions both over the apparition and during the encounter, showing the comet in a very steady state at the time of the encounter and demonstrating that the production rates deduced globally with IUE agreed with those deduced from localized in situ measurements with ICE. The coma was modelled in detail by Boice et al (GRL 13, 381).

Comet P/Halley's gaseous emission was first observed by Wyckoff et al (Nat 316, 241) in the spectra at 6 AU. This was substantially confirmed by Barker and Opal (ACM II, 481) and by Meech et al (Ic 66, 561).

The spectrum of the coma was studied from the spacecraft by Combes et al (Nat 321, 266; ASR 5, 127), who discuss the abundances of H_2O and CO_2 and the detection of CO and CH-compounds; by Krasnopolsky et al (Nat 321, 269; ASR 5, 143), who discuss OH, H_2O and CN and the existence of newly created radicals in excited states; by Moreels et al (Nat 321, 271), who discuss OH, NH, CN, C_3, CH, C_2, NH_2, and H_2O^+. The principal molecules discussed from the observations were H_2O, CO_2, OH, and CN. The neutral mass spectrometers measured an inverse square law for the density and a production rate of 10^{30} per sec, as discussed by Keppler et al (Nat 321, 273), Gringauz et al (Nat 321, 282; ASR 5, 165), and Krankowsky et al (Nat 321, 326), and showed that water was the dominant gas in the inner coma. Relative abundances were also deduced for a number of other species showing, e.g., that CO_2 was a few percent of water. Eberhardt et al (ESA 250/1, 383) showed that CO (and/or N_2) was a parent but was also produced in part by a very short-lived parent. Spatial profiles of CN, C_2, and OH were also obtained by Levasseur-Regourd et al (Nat 321, 341; ASR 5, 197).

The ultraviolet emitting species were monitored with IUE by Feldman et al (ESA 263, 39). UV observations were also carried out from rockets, by McCoy et al (Nat 324, 439), and by Woods et al (Nat 324, 436) who concluded that CO was a parent molecule. Lyman-alpha was monitored by Craven et al (GRL 13, 873) from Dynamics Explorer 1. Variations in this radiation were reported by Kaneda et al (Nat 321, 297 ; GRL 13, 833). The far UV region down to 150 nm was also investigated in detail by the space station Astron (Boyarchuk et al, AZhL 12, 696; ESA 250/1, 193). Schleicher et al (ESA 263, 31) set upper limits on OD, while Eberhardt et al (ESA 250/1, 539) found the same upper limit but also a lower limit requiring D/H enhancement over the interstellar value, not by more than about 10x. The D/H ratio of cometary water molecules was found to be 0.6 to 4.8 x 10^{-4}, which is similar to corresponding values in terrestrial oceanic water and atmospheres of several other planetary bodies. This result is of major importance for the relationship of comets to the solar system matter.

Photometry of optical species was reported by Catalano et al (AA 168, 341). Extensive spectrophotometric observations were conducted by Spinrad et al, Cochran and Barker, and Fink et al (ESA 250/1, 437, 439; ESA 250/3, 485), while high-resolution ($\sim$0.09 nm) spectra were secured with the 6-m telescope: about 500 spectrograms in the region 330-660 nm with exposure times 5-10 min (Afanasev et al, KTs 352). Observations of the N_2 1P system were reported by Mamadov (ATs 1987). Sherb et al (ASR 5, 279) observed H_2O^+, H-alpha, [OI], and NH_2 at very high spectral resolution with a Fabry-Perot. Kerr et al (ASR 5, 283) made similar observations. The [OI] + NH_2 blend was also resolved with an echelle spectrometer by Arpigny et al (ESA 250/3, 81; AA, in press). Using images in CN and C_2, A'Hearn et al (Nat 324, 649; ESA 250/1, 483) discovered jets of gas uncorrelated with the previously known jets of dust.

The infrared spectrum of H_2O was studied in detail by Mumma et al (Sci 252, 1523) and by Weaver et al (Nat 324, 441) and fitted with their excitation model. Knacke et al (ApJ 310, L49) reported the 3.35-micron emission by CH compounds, first detected by Combes et al (Nat 321, 266). Emission at this wavelength was also observed by Danks et al (ESA 250/3, 103), Wickramasinghe and Allen (Nat 323, 44), and Baas et al (ApJ 311, L97), who advocate organic compounds.

In preparation for P/Halley, the cometary radio emissions were reviewed by Snyder (AJ 91, 163) and modelled by Schloerb and Gérard (AJ 90, 1117). Surveys were performed by Galt (AJ 93, 747) and by Schloerb et al, Gérard et al, Mirabel et al, and Cordes et al (ESA 250/1, 583, 589, 595; ESA 250/3, 113). De Pater et al (ApJ 304, L33) reported unusual, stable structures in the map of OH. Observations of radio emission by HCN were reported by Bockelée-Morvan et al (AA 180, 253) and by Schloerb et al (ApJ 310, L55), both of whom found outflow velocities near 1 km/s but varying with r. The HCN varied significantly from day to day.

Variability of the gaseous abundances on the time scale of hours at the time of spacecraft encounters was discussed by Festou et al (Nat 321, 361) and by Schleicher et al (ESA 250/1, 565). Leibowitz and Brosch reported a 52-hour periodicity in the molecular abundances (Ic 68, 418), whereas Millis and Schleicher found a period of 7.37 days and an amplitude near a factor of two (Nat 324, 646). This was confirmed by Williams et al (MN 226, 1p) and Festou et al (AA, in press). Feldman et al reported a sudden outburst of gases rich in CO_2 (Nat 324, 433).

4 Cometary Plasma

The years 1985 and 1986 have been particularly exciting for the study of cometary plasma physics. This was because the in situ measurements made during the spacecraft encounters with comets Giacobini-Zinner and Halley have, for the first time, enabled many physical phenomena related to comet - solar wind interaction to be revealed.

TURBULENCE AT LARGE DISTANCES

At the approaches of the spacecraft to P/Giacobini-Zinner (within 2 x 10^6

km) and P/Halley (within 10^7 km), high levels of magnetic and plasma wave turbulences were recorded (Scarf et al and Smith et al, Sci 232, 377 and 382; Riedler et al and Neubauer et al, Nat 321, 288 and 352). This effect is the direct result of solar wind pickup of the newly born cometary ions which were observed by plasma instruments (Mukai et al, Balsinger et al, and Johnstone et al, Nat 321, 299, 330, and 344). The magnetic field turbulence at a frequency similar to the water ion gyrofrequency ($\sim$ 0.01 Hz) has been suggested to be excited by the ion beam instability from pickup of the water-group ions (Tsurutani and Smith, GRL 13, 263; Wu and Davidson, JGR 77, 5399). Associated with the high degree of turbulence ($\Delta B/B \sim O(1)$) is the presence of energetic heavy ions ($E > 100$ KeV) at large cometocentric distances ($r >$ a few million km) which is most probably indicative of acceleration processes, such as stochastic second-order Fermi acceleration effect (Hynds et al, Sci 232, 361; Somogyi et al and McKenna-Lawlor et al, Nat 321, 285 and 347; Gribov et al, ESA 250/1, 271). Within a few 100,000 km of the cometary bow shock, which was typified by a higher degree of plasma turbulence, rapid isotropization and thermalization of cometary ions, slow down and deflection of the solar wind plasma (Tsuratani and Smith, and Richardson et al, GRL 13, 259 and 415; Balsiger et al and Johnstone et al, Nat 321, 330 and 344; Coates et al, Nat 327, 489), the hardening of the energy spectra of the cometary ions might be the combined result of diffuse shock acceleration, shock compression and shock drift acceleration - in addition to the second-order Fermi process (Amata and Formisano, PSS 33, 1243; Ip and Axford, PSS 34, 1061).

CHARACTERISTIC FEATURES OF THE COMET - SOLAR WIND INTERACTION

The ICE spacecraft went through the tail of P/Giacobini-Zinner, hence providing important information on the structure of a cometary ion tail. The draped-field model of Alfvén (Tellus 9, 92) was basically confirmed. The peak value of the magnetic field was measured to be 60 nT (Smith et al, Sci 232, 382) which was comparable to the thermal pressure exerted by the cometary pickup ions (Siscoe et al, GRL 13, 287). A central current sheet, with a projected width of 1100 km along the spacecraft trajectory, was characterized by low magnetic field ($B \sim 5$ nT), low electron temperature ($T_e < 13{,}000$ K), and high plasma density ($N_e > 670$ cm^{-3}) according to the various plasma measurements (Bame et al, Meyer-Vernet et al, and Smith et al, Sci 232, 356, 370, and 382). The scale length of the bow shock (a subsolar point distance of about 5×10^4 km), when compared to theoretical model calculations, suggested an ougassing rate of 4×10^{28} molecules/s (Mendis et al, GRL 13, 239), which is compatible with the value derived from ground-based observations (Spinrad et al, ESA 250/1, 437). The large gas production rate of P/Halley (10^{30} H_2O/s) caused a much more extended solar wind interaction effect. For instance, energetic ions presumably of cometary origin were detected at the cometocentric distance of $5\text{-}10 \times 10^6$ km (Somogyi et al, Nat 321, 285). The bow shock was encountered at about 10^6 km from the comet. In agreement with theoretical predictions (Wallis, PSS 21, 1647; Schmidt and Wegmann, CPC 19, 309), the bow shocks at P/Giacobini-Zinner and P/Halley were found to be weak, with a Mach number on the order of 2 (see Galeev, ESA 250/1, 3).

The sunward passages of the Vega and Giotto spacecraft near P/Halley have revealed the existence of several boundary structures in the subsonic flow region inside the cometary bow shock. The so-called cometopause structure, which was first detected by the Vega 2 spacecraft at a cometocentric distance of approximately 1.6×10^5 km (Gringauz et al, Nat 321, 282), has the appearance of a rather narrow layer (width 10,000 km) separating the outer region which is characterized by solar wind plasma and the inner region of slow moving plasma of cometary composition, according to the reports by the Plasmag-1 experimenters (Gringauz et al, ESA 250/1, 93). Similar transition was seen by the Giotto plasma experiments but the structure seems to be more gradual than that reported by the Vega 2 Plasmag-1 experiment (Balsiger et al, Nat 321, 330). While the formation of such compositional transition has been interpreted in terms of charge-exchange loss of the solar wind plasma, the physical configuration of the cometopause is still to be clarified.

IONIZATION IN THE INNER COMA

Except for the observation of a suprathermal electron population in the inner coma of P/Halley during the Vega flyby measurements (Gringauz et al, Nat 321, 282), no clear signatures of enhanced electron impact ionization generated by energy transfer from the cometary pickup ions to the electrons, as suggested by the critical velocity ionization effect (Formisano et al, PSS 30, 491), were found in the comas of P/Giacobini-Zinner and P/Halley. The electron ionization rate, however, can be shown to be comparable to the photoionization rate in localized regions of P/Giacobini-Zinner's coma, while the corresponding electron impact ionization appeared to be lower at P/Halley, as derived by the electron analyser on Giotto (Lin, priv. comm.). Enhanced ionization is therefore not the most likely cause of the observed ion density profile, with a maximum at cometocentric distance of approximately 13,000 km, as detected at the Giotto encounter (Krankowsky et al and Balsinger et al, Nat 321, 326 and 330). The possibility exists that such plasma structure may be of non-stationary nature, resulting from changes in the solar wind conditions or the outgassing rate of the comet itself. Under steady state, the presence of a high electron temperature gradient would be effective in reducing the ion density inside the plasma peak (Ip et al, and Sauer and Baumgärtel, AA, in press), even though the issue of the electron temperature variation in the inner coma remains ambiguous.

MAGNETIC FIELD STRUCTURE

Various magnetic directional changes were encountered by the Vega and Giotto probes during their flyby observations (Riedler et al and Neubauer et al, Nat 321, 288 and 352). These changes reflected the sweeping of the interplanetary magnetic field structures by the cometary ionosphere. A dramatic discovery was made by the magnetometer experiment on the Giotto spacecraft as it reached an inbound distance of 4600 km from the cometary nucleus: the magnetic field was observed to drop from a value of 45 nT to effectively zero within a short distance ($\Delta r \sim 1300$ km) at the boundary of the diamagnetic cavity at 4700 km (Neubauer et al, Nat 321, 352). The formation of such a magnetic field-free cavity may be explained in terms of force equilibrium between the Lorentz force of the piled-up magnetic field and the ion-neutral drag (Cravens, ESA 250/1, 241; Ip and Axford, Nat 325, 418). At the crossing of this magnetic boundary, the ion temperature was observed to drop rapidly from 2600 K to as low as 300 K (Balsiger et al, Nat 321, 330; Schwenn et al, ESA 250/1, 225). The higher ion temperature outside the contact surface has been explained in terms of frictional heating by the plasma flow in the neutral coma (Haerendel, GRL, in press). Recent work on MHD model simulation by Wegmann et al (AA, in press) also indicates a plasma speed of 1 - 3 km/s and an ion temperature up to 3000 K between the diamagnetic cavity and a distance of 10,000 km.

NEUTRAL AND IONIC COMPOSITION OF THE COMA

In the inner coma region, the electron temperature was calculated to be between 10,000 and 20,000 K by Wegmann et al (AA, in press). As both Vega and Giotto probes were not equipped with devices capable of measuring cold electrons, experimental data on electron temperature, which is vital to ion chemistry modelling, are lacking. Nevertheless, interesting results on cometary neutral and ion composition in the inner and outer comas have been obtained by several theoretical groups. For example, the spatial distributions of several ion species - O^+, OH^+, H_2O^+, H_3O^+ (the most abundant ion in the inner coma) and S^+ - published in the preliminary report of the Ion Mass Spectrometer experiment on Giotto (Balsiger et al, Nat 321, 330), can be reproduced reasonably well (Boice et al, AA, in press). Another line of approach has been to evaluate the relative abundances of CH_4 and NH_3 relative to H_2O by comparing the theoretical results from gas phase chemistry to observed count rates of the relevant ion mass channels in the inner coma (Allen et al, AA, in press). These authors report ratios of production rates $Q(NH_3)/Q(H_2O) = 0.013$, and $Q(CH_4)/Q(H_2O) = 0.02$.

A surprise in the Giotto observations has to do with the large abundance of C^+ ions measured in the outer coma (Balsiger et al, Nat 321, 330). One suggestion is that these ions might have originated from a distributed source of atomic carbon; emission from the so-called CHON dust grains could be one possibility. It should be mentioned here that the CO molecules, whose production rate was about 15 percent of the H_2O production rate, were found to originate mostly from a distributed source (Eberhardt et al, ESA 250/1, 383). Evaporating dust grains could also be a potential source of the CO molecules. On the other hand, the fact that the reported CN and C_2 jets did not correlate spatially with dust jet structures could be explained by the electromagnetic perturbation of the trajectories of electrostatically charged submicron particles (Horanyi and Mendis, ApJ 294, 357) which may be the parents of the observed radicals. Flammer et al (EMP 35, 203) had also pursued the possible correlation of the brightness variations of P/Halley at large heliocentric distances ($r > 8$ AU) with electrostatic levitation of small dust grains from the surface of the nucleus as modulated by solar wind high-speed streams.

GROUND-BASED OBSERVATIONS

Accurate work by Ivanova et al (ESA 278, in press) allowed a determination of the H_2O^+/CO^+ abundance ratio in the ion tails of P/Giacobini-Zinner and P/Halley. It was found that this ratio was 2 for P/Giacobini-Zinner, and 0.5 and 0.25 for P/Halley at heliocentric distances $r = 1.5$ and 1.0 AU, respectively. Narrow-band filter imaging observations by Jockers et al (ESA 250/1, 59) have shown the potential of such kind of measurements in tracing clearly the dynamical activity and evolution of plasma structures in cometary ion tails, as described by Brandt and Niedner (ESA 250/1, 47). One particularly interesting result, obtained by Celnik (ESA 250/1, 53), is the tracking of the motion of ion tail condensations in CO^+ emission, which revealed a periodicity of generation of these large-scale plasma structures very similar to the rotation period of the comet nucleus of 54 hours. Such a temporal effect might have been closely related to the spin-modulation of the outgassing rate, and hence to the production rate of cometary ions. Feldman et al (Nat 324, 433) analyzed an outburst of the $CO_2{}^+$ emission in the ion tail, as observed by IUE on 18 March 1986. Whether such an outburst is typical of the generation of a CO^+ condensation propagating downstream in the fashion described by Celnik (ESA 250/1, 53) is still to be investigated.

Large-scale plasma phenomena were extensively recorded by the Large-Scale Phenomena Network of the International Halley Watch during the period November 1985 - June 1986. This apparition showed a rich display of disconnection events, with 19 obvious cases and perhaps a dozen more. The 19 obvious events show a clear association with sector boundary crossings. This fact and the detailed study of the 8 March 1986 event by Niedner and Schwingenschuh (ESA 250/3, 419), utilizing both in situ and ground-based data, indicates that the sector boundary/frontside reconnection model of Niedner and Brandt (ApJ 223, 655) has survived crucial tests and, so far, is favoured. Models of disconnection events, however, are expected to be an active area of cometary plasma research. Mention may also be made here of the detailed analysis published by Jockers (AAS 62, 791) on the ion tail phenomena of comet 1973 XII Kohoutek, as observed on wide-field photographs secured around the world on 17 consecutive days, 9 - 25 January 1974.

THEORETICAL WORK

Many more efforts than could be reported here have been devoted to the interpretation of the cometary plasma - solar wind interaction, and we can only mention a limited number of publications, mainly of a general character, such as the reviews by Galeev and Lipatov (ASR 4, 229); Ip et al (Advances in Space Plasma Physics, ed Buti, Singapore 1985, 1); and Galeev (ESA 250/1, 3), which contain many other references. The last mentioned survey was already prepared in the light of the results obtained from the recent cometary space missions. Several reviews of interest have also been presented by Wallis on quasi-fluid and magneto-fluid theories, Kömle and Lichtenegger on numerical modelling, Phillips et al on similarities and differences between the solar wind interactions with comets and with Venus, Baumgärtel et al on non-stationary models, and Sagdeev et al on plasma instabilities due to mass loading (Field, Particle and Wave Experiments on Cometary Missions, eds Schwingenschuh and Riedler, Vienna 1985, 7, 19, 37, 54, and 74). The plasma processes and structures occurring in the interaction of the solar wind with comets and with other neutral atmospheres in the solar system have been reviewed and compared by Ip (ESA 235, 65), who suggests a number of related major objectives for future spacecraft missions.

The stability of the cometary ionopause has been studied extensively by Ershkovich et al (ApJ 311, 1031 and references therein), while cometopause instability and a possible mechanism of structure formation in ionic tails have been discussed by Ioffe (AZh 64, 145). Recent contributions on the phenomenon of tail detachment have been presented by Gerasimenko (KTs 361), Obukhov et al (AZhL 12, 942), and Russell et al (JGR 91, 1417). A chemico-physical model combining in a consistent way the description of the chemical evolution of the expanding coma with the MHD treatment of an axisymmetric solar wind interaction has been developed and applied to P/Giacobini-Zinner (Boice et al, GRL 13, 381) and P/Halley (Wegmann et al, AA, in press).

5 Cometary Dust

Useful reviews of our pre-Halley knowledge on various topics of the study of cometary dust have been published: properties of dust particles in the coma and tail, observational evidence (Lamy, ACM II, 373); cometary polarimetry (Dobrovolsky et al, EMP 34, 189); ices in grains (Campins, NASI 156, 443); dust and neutral gas modelling of the inner coma (Gombosi et al, RG 24, 667); predictions on P/Halley dust and gas environment (Divine et al, SSR 43, 1); and predictions of the impact rate by larger dust particles (Hajduk, ACM II, 497).

Systematic studies of relatively faint comets have become possible thanks to the use of large telescopes at several observatories. Thus, for example, a comparison of the dust characteristics of ten short-period comets has been made by Hanner (ASR 4, 189). The mean size and albedo of the grains are rather similar in these objects, with the exception of P/Crommelin whose grains are larger and appreciably darker. In a systematic investigation of the wavelength distribution of the light scattered by a dozen of comets, Jewitt and Meech (ApJ 310, 937; ESA 250/2, 47) have found differences in grain properties which appear to be intrinsic to the individual objects (different size distribution or different composition ?).

A detailed review of the first analyses and results regarding the dust environment of P/Halley (S/C experiments; jets streamers, antitail, sunward spike; IR observations; effects of irradiation) has been given by Sekanina (ESA 250/2, 131). Grün et al (ESA 278, in press) have presented a critical discussion of the existing models of the dust coma, and emphasized the recently discovered properties and phenomena related to the cometary dust.

INFRARED OBSERVATIONS

Routine infrared monitoring of the dust coma has been carried out from several ground-based (near IR) and airborne (far IR) observatories, on P/Crommelin (Eaton and Zarnecki, MN 217, 659; Hanner et al, AA 152, 177), P/Churyumov-Gerasimenko (Hanner et al, Ic 64, 11), and comet 1982 I Bowell (Hanner and

Campins, Ic 67, 51). Further analysis of IRAS S/C data led to the discovery of dust trails behind and ahead of various comets in their orbital planes (Sykes et al, Sci 232, 1115).

P/Giacobini-Zinner and P/Halley were the first comets ever imaged from the ground with infrared arrays. The combination of nearly simultaneous visual and thermal IR maps yields the spatial distribution of the albedo, which is interpreted in terms of large, dark, fluffy particles (Hammel et al, ESA 250/2, 73). An extensive program has been developed for P/Halley and a preliminary review has been prepared by Hanner (ASR 5, 325); see also Campins et al (GRL 13, 295), Harvey and Campins (ASR 5, 335), Knacke et al (ApJ 310, L49), Tedesco et al (ApJ 310, L61), Tokunaga et al (AJ 92, 1183) and numerous reports in ESA 250/2, 81 to 130. The thermal emission was found to be dominated by relatively large particles (> 1 µm); the grains exhibited a low average albedo. Emission features were detected in the 3 µm and 10 µm spectral regions, especially from the IKS spectrometer on board Vega (Combes et al, Nat 321, 266). The emission near 3.4 µm is indicative of organic matter (large molecules or small grains ?). The dust production was found to vary strongly with time.

POLARIMETRIC OBSERVATIONS

Physical properties of the dust grains can be inferred from polarimetric observations of comets, through the phase angle and wavelength dependence of the polarization. Recent analyses on this subject have been presented by Myers and Nordsieck for comet 1982 VI Austin and P/Churyumov-Gerasimenko (Ic 58, 431); by Myers for P/Kopff and P/Tempel 1 (Ic 63, 206). Telescopic linear polarization measurements have been carried out in 1985/86 over P/Halley's coma in visible light by Bastien et al (MN 223, 877), Dollfus et al (ESA 250/2, 41), Dzhapiashvili et al (ESA 250/3, 191), Kiselev et al (ESA 250/3, 29), Le Borgne et al (ESA 250/1, 571), and Mukai et al (ESA 250/2, 59). Circular polarization measurements have been reported by various authors, in particular by the observers at the Soviet-Bolivian Observatory near Taricha (Bolivia), who quote values of ~ 0.004 for April 1986 (Guralchuk et al, KFNT 3/2, 89). The same team found a gradual turning of the polarization plane in a narrow phase angle (α) around the inversion angle. This effect was interpreted as a direct result of the orientation of prolate particles (Guralchuk et al, KFNT 3/3, 93). Detailed discussion as well as analysis of a large number of linear polarization observations at various phase angles were presented by Beskrovnaya et al (ESA 278, in press). The particles appeared to be of micrometer dimensions and to have physical properties like those of graphite grains. Much larger sizes were advocated by Morozhenko et al (Ic 66, 223). The distribution function of grain sizes A was found by Dobrovolsky (KFNT 2/2, 35) to be of the form A^{-s} with $s = 3.5$, in accordance with Giotto measurements. Infrared data have been obtained by Brooke et al (ESA 250/2, 87); polarization measurements over the tail have been performed by Lamy et al (ESA 250/2, 69); the OPE photopolarimeter on board Giotto spacecraft has recorded in situ polarization measurements in the coma (Levasseur-Regourd et al, Nat 321, 341; ASR 5, 197).

A meeting of most of these observers was held in Paris in March 1987. There is a good agreement for the phase angle dependence of near-nucleus observations, typically with a minimum of -0.017 at $\alpha = 10^{\circ}$, an inversion at $\sim 21^{\circ}$, and a value of ~ 0.2 at 73°. The question of the wavelength dependence is still disputed, however; it seems that there was a change in the colour dependence of polarization as the comet passed through different phase angles. Various results on polarization are to appear soon in AA.

IN SITU MEASUREMENTS

Direct measurements of Halley's dust have been performed by the dust instruments on board the Halley spacecraft. Significant new data on the chemical composition and the mass distribution have been obtained (Vaisberg et al, Mazets et al, Simpson et al, Kissel et al, and McDonnell et al, Nat 321, 274, 276, 278, 280, 336, and 338). The dust was found to be composed of silicates and refractory carbonaceus material in varying proportions. Many particles (referred to as CHON particles) are rich in low-Z elements: hydrogen, carbon, nitrogen and oxygen (Kissel and Krueger, Nat 326, 755). The slow release of these elements from the grains in the coma has been invoked to explain the ground-based observations of CN and C_2 jets (A'Hearn et al, ESA 250/1, 483). The average abundance of the heavier elements is chondritic within a factor of two. The composition of cometary dust grains, mainly the presence of organic matter, lends support to models emphasizing the interstellar connection of cometary materials. Although the smallest grains which are of sizes comparable to interstellar grains are by far the most numerous in the coma, they contribute little mass to the comet's total dust output, the major part of it being contained in the biggest particles recorded (McDonnell et al, ESA 250/2, 11). Over the period of one week the three Halley space probes recorded dust fluxes which varied over about one order of magnitude.

NON-UNIFORM NUCLEUS ACTIVITY AND DUST JETS IN THE COMA

Images taken by the television cameras on board the Vega 1, 2 and Giotto spacecraft (Sagdeev et al and Keller et al, Nat 321, 259 and 320) showed dramatically the irregularities of the dust emission from the nucleus. Only a small fraction (about 20 percent) of the sunlit surface actively emits dust. These active regions are the origin of jets or fans which are seen inside the coma by ground-based visual observers. Because of the inferior intensity resolution of photographic plates, only sophisticated digital image enhancement techniques reveal structures in the photographed coma (Larson and Sekanina, AJ 89, 571). From the analysis of photographs taken during the 1910 apparition of P/Halley, Sekanina et al (AJ 89, 1408; AJ 92, 462; Nat 321, 357) derived the spin vector, rotation period and distribution of active areas on the nucleus. However, recent ground-based observations (see, e.g., Grün et al, Nat 321, 144 and references on periodic variations quoted in the preceding chapters), and inclusion of the in situ data from the Halley spacecraft have shown that the rotational state of P/Halley's nucleus cannot be described as a simple spin about a fixed axis (see Wilhelm, Nat 327, 27 and references therein). The anisotropic dust emission together with the complex rotational state of the nucleus explains strong and irregular variability of the brightness, both of the nucleus at large heliocentric distances (West and Pedersen, AA 138, L9; Festou et al, AA 169, 336) and of the coma in the inner solar system (Schleicher et al, ESA 250/1, 565 and references therein; Cosmovici et al, ESA 250/2, 151). Dusty outbursts at large distances and jet development near the Sun were also reported by Dobrovolsky (KFNT 2/1, 66) and by Dobrovolsky et al (ESA 250/3, 31), respectively.

THEORETICAL INVESTIGATIONS

Different aspects of the history of solid particles from their leaving the nucleus were considered, such as possible pseudo-fluidization of the outer part of the nuclear dust envelope (Shulman, KFNT 1/5, 53); dust halo formation (Gombosi and Horányi, ApJ 311, 491); expected properties of the icy grain halo (Kajmakov and Lyzunkova, KTs 320 and 341; Andrienko and Mishchishina, AZh 63, 335; Crifo and Emerich, NASI 156, 429); properties of dirty ice grains (Mukai et al, ASR 5, 339; AA 167, 364); generalization of the Finson-Probstein dust tail theory (Chernyj and Sizonenko, KFNT 2/3, 52; Chernyj, KFNT 2/6, 64); dynamics of charged dust particles (Horányi and Mendis, JGR 91 A1, 335; ApJ 308, 800); short-wave radiation and multi-charged ion generation due to high velocity collisions of cometary and zodiacal dust particles (Ibadov, IAUC 85, 365; ESA 250/1, 377).

The problems of cometary origin and of further evolution of cometary dust particles involve relationships to the interstellar matter; meteoroids and meteor streams; and the zodiacal dust cloud. Recent progress in the relevant research areas is reviewed in the reports of IAU Commissions 34, 22, and 21, respectively.

6 Origin and Evolution of Comets

ORIGIN

Comet accretion theories and nuclear models have been discussed in the section on Cometary Nuclei. Here we shall consider mainly the progress in investigating the time scales and locations of comet nuclei formation.

Prialnik et al (ApJ 319, 993) have found a constraint on the formation time of comets from the absence of major effects of ^{26}Al heating. The evidence for very low densities (Greenberg, ACM II, 221; Rickman, ESA 249, 195; Bertaux and Abergel, BAAS 18, 794; Rickman et al, ESA 278, in press) implies that cometary nuclei are homogeneous without any major core-mantle differentiation, but also suggests a very gentle formation mechanism.

Support for an accretional origin was found by Donnison (AA 167, 359) from the cometary magnitude distribution. Modelling of cometary nuclei as accretional aggregates of planetesimals formed by gravitational instabilities was done by Yamamoto and Kozasa (ISAS 364) with the result that most comets should have formed at several 10^2 AU. Grain accretion followed by gravitational instability may also occur in wind-driven shells around protostars according to Bailey (Ic 69, 70). A new theory of cometary nuclei condensation in the protosolar nebula based on the thermodynamic compatibility concept was developed by Shulman (Cometary Nuclei, Moscow 1987). Molecular ion clusters of both signs were hypothesized to have been stored during this early stage and to serve as additional energy sources nowadays.

Icy crust eruption has been proposed as the origin mechanism from massive transplutonian planets by Radzievskij (KFNT 3/1, 66), and from satellite-like, Ganymede-type bodies by Drobyshevskij (IPTI 1132). Vorontsov-Velyaminov recognizes the possibility of different ways of nucleogenesis, but believes the catastrophic destruction of the hypothetical planet Asteron to be the most probable one, and gives some new arguments (AZh 63, 181).

OORT'S CLOUD

The formation of the Oort cloud was reviewed by Fernández (IAUC 83, 45), its structure and observational background by Oort (Sterne 61, 270), and its evolution in more general terms by Weissman (IAUC 83, 87; SSR 41, 299; ACM II, 197) and Oort (Obs 106, 186). Survival of the cloud against the effect of GMC encounters was claimed by Hut and Tremaine (AJ 90, 1548) but appeared less certain in the work by Bailey (MN 218, 1). The treatment of stellar perturbations was improved by Remy and Mignard (Ic 63, 20). The role of the Galactic tidal field has now been recognized as important, perhaps even dominant (Heisler and Tremaine, Ic 65, 13; Heisler et al, Ic 70, 269). Injection of comets into the planetary system by Galactic tides was investigated by Torbett (MN 223, 885) and demonstrated from orbital statistics by Delsemme and Patmiou (BAAS 18, 799). New orbital computations for long-period comets were made by Everhart and Marsden (AJ 93, 753).

A dense inner core of the Oort cloud remains to some extent speculative but has found support from various arguments. Comet showers (review by Hut et al, Nat 329, 118) would depend on the existence of such a core, as explored by Fernández and Ip (Ic 71, 46). Infeed to the outer planetary region from such a core was shown by Bailey (Nat 324, 350) to yield a promising source for maintaining the short-period comet population. Observational verification of the structure of the Oort cloud, including its inner core, was considered by Baum et al (BAAS 17, 690; PASP 97, 899) and by Marochnik and Sholomitskij (IKI 942).

EVOLUTION

The problem of the lifetimes and disappearance of long-period comets was examined by Kresák (BAC 35, 129; IAUC 83, 279). Their fading was studied by Bailey (MN 211, 347) who suggested an explanation in terms of a thermal shock (IAUC 83, 311). Chemical differentiation driven by sublimation was modelled by Houpis et al (ApJ 295, 654), and effects of cosmic-ray irradiation in the Oort cloud producing severely altered material including organic refractories in meter-thick surface layers were suggested by Johnson et al (ESA 250/2, 269). The question whether P/Halley may have an irradiation-driven crust was also raised by Sekanina (ESA 250/2, 131).

Nevertheless, dust coverage appears as the main influence on short-period comet evolution (Fernández, Ic 64, 308), but may be restricted to comets that are not perturbed into too small perihelion distances (Nazarchuk and Shulman, KM 35, 27). Lifetimes and fading of short-period comets were reviewed by Kresák (IAUC 83, 279; Evolution of Small Bodies of the Solar System, Bologna 1987, 202). A typical lifetime of 300 - 500 revolutions thus appears likely; while there seem to be transient dormant phases (Kresák, ESA 250/2, 433), progressive fading can hardly be observed (Kresák and Kresáková, ESA 278, in press). Modelling work related to the photometric evolution of short-period comets was done by Dobrovolsky et al (DANT 27, 189; ESA 250/2, 389), Nazarchuk and Shulman (KM 35, 11), and Markovich (KFNT 2/1, 70). Marsden (IAUC 83, 343) reviewed the problem of nongravitational forces and indicated that "wild" and increasing forces are characteristic of comets soon to disappear. This would be indicative of a disintegration process, but Rickman et al (ESA 278, in press) found an opposite trend on the average for newly captured comets, interpreted by means of gradual dust coverage.

A continuation of the well-known Vsekhsvyatskij's cometography has been undertaken by Andrienko and Karpenko (Physical Characteristics of Comets 1976-1980, Moscow 1987). Short-term (1800-2000) orbital evolution, observing geometry at past and future perihelion passages, and various events of evolutionary significance can be found in the Catalogue of Short-period Comets (Belyaev et al, Bratislava 1986), while a longer period of orbital changes (1585-2406) is covered by the Long-term Evolution of Short-period Comets (Carusi et al, Bristol 1985).

COMETS AND ASTEROIDS

Evolution of comets into asteroids was reviewed by Rickman (IAUC 83, 149), and Hartmann et al (Ic 69, 33) pointed out that asteroids believed to be of cometary origin on dynamical grounds (Hahn and Rickman, Ic 61, 417) tend to belong to spectral classes D, P or C, indicating a relatively remote place of origin. Comet-asteroid relationships were also reviewed by Hartmann (ACM II, 191) and A'Hearn (ACM II, 187). A possible comet-asteroid connection for 3200 Phaethon was disussed by Cochran and Barker (Ic 59, 196) and Green et al (MN 214, 29p). Davies (MN 221, 19p) found a probable cometary association for the three Apollo asteroids discovered by IRAS. The low-activity comets P/Arend-Rigaux and P/Neujmin 1 were extensively observed in the visual and IR, and their nuclei proved to be big, black and hot (Tokunaga et al, ApJ 296, L13; Millis et al, BAAS 17, 688; Veeder et al, BAAS 17, 688 and AJ 94, 169; A'Hearn et al, PASP 97, 892; Birkett et al, MN 225, 285; Campins et al, ApJ 316, 847; Brooke and Knacke, Ic 67, 80).

7 Minor Planets

During the past three years, the explosion in research on asteroids has continued at a pace which precludes listing of all, or even most, papers. The reader is referred to such bibliographical sources as Astronomy and Astrophysics Abstracts (subject 098: Minor Planets) for complete listings. During the last triennium, traditional techniques (e.g., photometry, spectrophotometry, and thermal IR) have been improved, and several new techniques have been applied to a significant number of asteroids (e.g., radar, occultations, speckle interferometry, microwave and UV wavelength observations).

ASTEROID SURVEYS AND PHYSICAL OBSERVATIONS

The Infrared Astronomical Satellite mapped essentially the entire sky in four channels, from 12 to 100 µm wavelength, during 1983. Green et al (Ic 65,

517) and Davies (MN 221, 19p) discuss the results of the search for near earth asteroids in the IRAS data. The first draft of the results of the main belt asteroid survey (IRAS Asteroid and Comet Survey, ed Matson, JPL D-3698) has been issued, giving observed IR fluxes for 1811 known asteroids. In addition to these data alone, the IRAS project has stimulated progress in ground based observations and interpretations. A new compilation of ground-based data is being assembled in support of the IRAS project (Tedesco, ACM II, 13). The zodiacal dust bands discovered by IRAS (Low et al, ApJ 278, L19) have been interpreted by Dermott et al (Nat 312, 505) as being due to collisional debris associated with the largest Hirayama families. The ratio of the flux from these bands to the total of the zodiacal cloud is consistent with the hypothesis that much, if not most, of the zodiacal dust is asteroidal in origin, rather than cometary. Sykes and Greenberg (Ic 65, 51) have offered an alternative hypothesis for the dust bands as remnants of recent collisions within the asteroid belt.

Perhaps the most dramatic asteroid discovery by IRAS was 1983 TB, now permanently named 3200 Phaethon, an asteroid which appears to be the parent body of the Geminid meteor stream. Cochran and Barker (Ic 59, 296), Green et al (MN 214, 29p), and McFadden et al (PASP 97, 899) have looked at the visual and near IR spectrum of Phaethon for evidence of cometary characteristics, without apparent success. They conclude that Phaethon is more or less similar to other near earth asteroids. Thus we are led to conclude either that comets evolve into rather unexpected taxonomic classes of asteroids (e.g., S, Q), or that asteroids as well as comets can have associated meteor streams. The IRAS dust bands would further argue for the latter possibility.

Brown and Morrison (Ic 59, 20) report diameters and albedos for 36 more asteroids, based on thermal IR observations. Lebofsky et al (Ic 68, 239) have refined the standard thermal model, based on new diameters of 1 Ceres and 2 Pallas obtained by occultation observations (see below). Brown (Ic 64, 53) has also included the effects of ellipsoidal geometry in models used to interpret thermal data.

NEW OBSERVING TECHNIQUES

In the past three years, the number of asteroids observed by radar has nearly doubled, from about 20 to over 40, through the efforts of Ostro and his co-workers (Ostro et al, Ic 60, 391 and Sci 229, 442; Ostro, PASP 97, 877). These observations have yielded estimates for the equatorial profiles of a few asteroids, constraints on pole positions, estimates of surface roughness and of metal content/porosity.

Occultations of stars by at least six asteroids were reported in the last three years (see report of Commission 20). We note here only one, by 1 Ceres, which is of particular interest in physical studies. Millis et al (BAAS 17, 729; PASP 97, 900; Ic, in press) report a new diameter for Ceres, which has been used in the thermal model revision mentioned above, and also derive the flattening and mean density for Ceres. The mean density, 2.7 g/cm^3, is the same as earlier derived for 2 Pallas. The flattening, along with the above density, is consistent with the hypothesis that Ceres is a homogeneous body with a figure of hydrostatic equilibrium.

Another new technique which has come into use recently is speckle interferometry. This technique has been applied to search for satellites and measure the size and shape of a few asteroids. Drummond and Hege (BAAS 16, 922; Ic 67, 251) and Drummond et al (Ic 61, 132; Ic 61, 232) report results for the asteroids 4 Vesta, 12 Victoria, 433 Eros, 511 Davida, and 532 Herculina.

Several papers report observations at new wavelengths. It is perhaps too soon to judge the worth of these new observations, but the range of new techniques being applied is encouraging. Seidelmann et al (CM 34, 39) report observations of thermal emission of asteroids at microwave wavelengths with the VLA. They were primarily concerned with astrometric measurements, but the observations also provide information about the physical nature and sizes of asteroids. Lebofsky et al (Ic 63, 192) report a first detection of an asteroid, 10 Hygiea, at the submillimeter wavelengths of 370 and 770 µm. Butterworth and Meadows (Ic 62, 305) report spectral observations of 28 asteroids in the UV range from 0.21 to 0.32 µm with the IUE. Finally, Albrecht and Schober (ACM II, 25) contemplate the range of observations which will become possible with the Hubble Space Telescope.

SPECTROPHOTOMETRY AND POLARIMETRY

Spectrophotometric observations and interpretations have proceeded at a vigorous pace. In addition to mapping out compositional classes as a function of location in the asteroid belt, two major issues currently motivating these studies are to determine the sources of near earth asteroids, and of various meteorite classes, particularly the ordinary chondrites. This most common of meteorite types seems to be spectrally distinct from all but perhaps a few asteroids. The largest project reported is the Eight Color Asteroid Survey ECAS, covering the spectral range from 0.34 to 1.04 µm, with observations of 589 objects (Zellner et al, Ic 61, 355). Tholen (PhD Dissertation, Univ. Arizona 1984) has used the ECAS data, plus radiometric albedo data, as a basis for a new taxonomic system. McFadden et al (Ic 59, 25) report spectrophotometry of 17 near earth asteroids, directed toward determining the sources of this class of bodies. Gaffey (Ic 60, 83) has looked for rotational variation of the spectrum of 8 Flora as evidence of differentiated units on the surface. Feierberg et al (Ic 63, 183) have observed 14 main-belt C class asteroids in the 2.3 - 3.3 µm spectral range for the spectral signature of water of hydration, which they find in varying degrees in 9 of the spectra. Vilas and Smith (Ic 64, 503) have observed the spectra of 19 outer main belt asteroids in the 0.5 - 1.0 µm range. Golubeva et al (AZh 63, 1179) and Golubeva (AZhL 12, 801) report spectrophotometry of the asteroids 4 Vesta and 3 Juno, respectively.

Bel'skaya et al (AZhL 11, 286 and 13, 530; KFNT 3, 19) report multicolour polarimetry of several asteroids, to search for spectral and rotational dependences of polarization.

LIGHTCURVES, SHAPES AND ROTATION

Photoelectric lightcurve observations have been reported in ever increasing numbers. Lagerkvist et al (Uppsala Obs. Report 36) present a bibliographical listing of all lightcurve publications, along with aspect data for each lightcurve published. Another publication by Lagerkvist et al (Asteroid Photometric Catalog, Rome 1987) contains the actual lightcurves as published. The authors plan to update these listings every year or two, and to make them available in magnetic tape form. Binzel (MPB 14, 39) has compiled a summary of all known unpublished lightcurve data. The reader is referred to these publications for complete listings of photoelectric observations. Harris (ACM II, 35) reviewed the current status of rotation statistics. A few lightcurve results deserve mention. Binzel (PhD Dissertation, Univ. Texas 1986) reports rotational lightcurves of over 100 asteroids, including one, 1220 Crocus (also reported in Ic 63, 99), with a lightcurve period of over 30 days. He suggests that this might be a period of spin axis precession, induced by the gravitational effects from a satellite, rather than a rotation period. Weidenschilling et al (Ic 70, 191) report a total of 257 lightcurves of 26 rapidly rotating asteroids. New lightcurves and rotation periods have been determined, among others, by Zeigler and Florence (Ic 62, 512) as a result of a high-school teaching project. Wisniewski and McMillan (AJ 93, 1264) report some of the first asteroid lightcurves obtained by CCD photometry. The technique should allow accurate photometry to perhaps 2 or 3 magnitudes fainter than previously possible, with a given telescope. Lagerkvist and Williams (AAS 68, 295) have used observations from the Carlsberg Meridian Circle on La Palma to construct composite lightcurves and phase relations for 51 asteroids.

Recent lightcurve observations have emphasized pole and shape studies, beyond just simply determining rotation periods. Magnusson (Ic 68, 1) has determined 20 spin axis orientations using a combination of epoch and magnitude-aspect methods. Zappalà and Knežević (Ic 59, 436) and Zappalà and DiMartino (Ic 68, 40) report 14 and 10 pole positions, respectively, by the magnitude-aspect method. Lupishko et al (VKU 278, 51; KFNT 3, 57) report senses of rotation for 8 asteroids. Smaller numbers of determinations have also been reported by Koshkin (Odessa Obs.), McCheyne et al (Univ. Leicester), Barucci et al (IAS Rome), Binzel (Univ. Texas), Taylor et al (Univ. Arizona), and Lambert (State Univ. New Mexico). New theoretical approaches for determining shapes and pole orientations from lightcurves have been discussed by Ostro and Connely (Ic 57, 443), Lumme et al (ACM II, 55), Pospieszalska-Surdej and Surdej (AA 149, 186), Surdej et al (AA 170, 167), and Koshkin (KFNT 2, 44). Barucci and Fulchignoni (ACM II, 45) review their work in laboratory simulation of asteroid lightcurves as they relate to shape studies.

COLLISIONAL EVOLUTION

Theoretical and laboratory studies of the collisional evolution of the asteroid belt have progressed considerably in the last three years. Davis et al (Ic 62, 30) have developed a new numerical model to simulate asteroid distributions, and using as observational constraints the properties of the major asteroid families and of Vesta's preserved basaltic crust. The number distribution of asteroids has been investigated by Ishida et al (PASJ 36, 357), Donnison and Sugden (MN 210, 673), and Zhou et al (PPMO 3, 22). Asteroid families have been increasingly used as natural experiments on large-scale collisions and to probe the interior composition of the presumed parent bodies (Zappalà et al, Ic 59, 261; Farinella et al, ACM II, 109; Davis, MSAI 57, 87; and Chapman, MSAI 57, 103). Problems in the derivation of proper orbital elements which could hamper these studies have been pointed out by Knežević (ACM II, 129) and Carpino et al (Ic 68, 55). Binzel (PhD Dissertation, Univ. Texas 1986) discovered differences in the mean rotation rates, dispersion about the mean, and mean lightcurve amplitudes between the Eos and Koronis families, suggesting that the Koronis family is collisionally younger than the Eos family. Catullo et al (AA 138, 464) have estimated the shape distribution of asteroids from lightcurve amplitudes. New laboratory experiments on high-velocity impacts have been carried out and analyzed by comparing the fragment properties with those of asteroids (Cerroni, MSAI 57, 13; Fujiwara, MSAI 57, 47; Capaccioni et al, Nat 308, 832, and Ic 66, 487; Fujiwara, Ic 70, 536). Many difficult problems arise when laboratory results are to be scaled to asteroidal sizes, and some critical and poorly tested assumptions are still needed for this purpose (Davis et al, Ic 62, 30; Holsapple and Housen, MSAI 57, 65). Recently, interesting new evidence on the collisional evolution of asteroids has been provided by meteoritical studies, whose results appear to support the idea that many asteroids were disrupted by collisions and subsequently reassembled into gravitationally bound "rubble piles" (Taylor et al, Ic 69, 1; Grimm, JGR 92, 2022; Scott et al, JGR 90, D137).

Regarding the origin and early evolution of the asteroid belt, Davis et al (Ic 62, 30) and Farinella et al (MN 216, 565; ACM II, 121) independently reach the conclusion that the collisional erosion of the asteroid belt has been only modest, thus the original mass in the zone was only at most a few times its present value. Interesting similarities (implying genetic connections) among C and D-type asteroids, comet nuclei, and small outer satellites of the giant planets have been pointed out by Hartmann (ACM II, 191), and Hartmann et al (Ic 69, 33). O'Dell (Ic 67, 71) has proposed a possible mechanism to form comet nuclei from material lying originally in the asteroid belt.

8 Spacecraft Missions to Comets and Asteroids

PAST MISSIONS

The spacecraft encounters of comets Giacobini-Zinner and Halley in 1985 and 1986, respectively, marked the beginning of a new era in cometary research.

The various activities in space were coordinated by the European Space Agency (ESA), Intercosmos of the USSR Academy of Sciences, the Japanese Institute of Space and Astronautical Science (ISAS) and the U.S. National Aeronautics and Space Administration (NASA), through the Inter-Agency Consultative Group for Space Science (IACG). Coordination of the ground-based observing activities was provided through the International Halley Watch (IHW). The single goal of both IHW and IACG was to maximize the overall scientific outcome of the uncountable efforts in all parts of the world to study Halley's comet from the ground and from space in the most comprehensive way.

Launched in 1978, the International Sun-Earth Explorer No. 3 (ISSE 3) completed after four years its mission as monitor of interplanetary space about 1.5 million km upstream from the earth, and was then redirected to comet intercept duty. After a total of 37 propulsive and 5 lunar gravity assist maneuvers the spacecraft, then renamed International Cometary Explorer (ICE), was sent on course towards P/Giacobini-Zinner. The last maneuver was a close lunar swingby on 22 December 1983, and the comet was encountered on 11 September 1985. ICE passed through the cometary tail at a distance of 7800 km from the nucleus of P/Giacobini-Zinner before continuing its journey towards P/Halley, which it passed on 25 March 1986, upstream at a distance of 28 million km.

Launched in 1984, the two Vega spacecraft started with the exploration of Venus, which they encountered on 15 June 1985 (Vega 2) and 11 July 1985 (Vega 1), and deployed a part of their instrumentation there (see report of Commission 16). In the last phases of their flight to P/Halley, the two Vegas also served as pathfinders for the Giotto spacecraft, enabling it to achieve the desired final cometary flyby distance of 600 km on the sunward side, with a deviation of just 5 km. This Pathfinder Project involved the participation of NASA in determining the exact positions of the two Vegas by the Deep Space Network using very-long-baseline interferometry techniques. Brief information on the Halley encounters is summarized in the following table. (The Japanese spacecraft Suisei and Sakigake were formerly called Planet-A and MS-T5, respectively.)

Flight parameters of the comet Halley fleet :

Spacecraft	Launched by	Launch date (UT)	Closest approach (UT)	Flyby velocity (km/s)	Flyby distance (km)
Vega 1	USSR	15 Dec 1984	6 Mar 1986	79.2	8,890
Suisei	Japan	19 Aug 1985	8 Mar 1986	73.0	151,000
Vega 2	USSR	21 Dec 1984	9 Mar 1986	76.8	8,030
Sakigake	Japan	9 Jan 1985	11 Mar 1986	75.3	6,990,000
Giotto	ESA	2 Jul 1985	14 Mar 1986	68.4	605
ICE	USA	12 Aug 1978	25 Mar 1986	60.0	28,000,000

The extensive scientific outcome of these missions is described in detail in the previous chapters of this report, arranged by topics. The highlights can be summarized as follows.

ICE provided a wealth of important data on the extent of the comet's influence on the interplanetary medium and gave in-situ fields and particle data in the comet's tail. In a broad outline, the pre-encounter theories of the plasma structures were essentially confirmed, but a few surprises occurred. The effect of cometary ions on the solar wind (pickup ions) were seen as far as 28 million km from the nucleus, indicating that the influence of P/Halley on the interplanetary medium would be noticeable by the Halley probes much earlier than originally anticipated, almost a day before the actual encounter.

The Halley missions essentially confirmed Whipple's model of a comet nucleus. The Vega and Giotto cameras showed a peanut-shaped body, both larger (about 16x8x8 km) and darker (albedo lower than 0.04) than previously thought, making it one of the darkest known objects in the solar system. Gas and dust emanate in form of jets from only a few regions on the nucleus, while the rest is covered by a dark crust. Much of the cometary dust is organic material. Particles as small as 10^{-17} g, covering a broad variety of chemical composition, were detected in considerable quantity, all of them reportedly fluffy rather than compact. At the time of the Giotto flyby, the total gas production was 6.9×10^{29} mol/s, of which 80 percent were water molecules. As already shown by ICE, the theories about the nature of the interaction of comets with the solar wind were essentially confirmed. There is a contact surface near 5000 km, inside which the solar wind does not penetrate and cometary ions flow freely outward, and a bow wave near 400,000 km where the inflowing solar wind is slowed down substantially by cometary ions.

FUTURE MISSIONS

Following these spectacular, but still reconaissance-level cometary flybys, ISAS considers a cometary flyby connected with a coma sample return. NASA plans to initiate an even more comprehensive exploration by conducting a close flyby of a main-belt asteroid, followed by a multi-year rendezvous with a short-period comet (CRAF mission) in the early 1990s, to study the comet both during quiescent and active phases. and to deploy a lander/penetrator into the surface of the comet. P/Tempel 2 is currently the main candidate for the target object. A joint project of France, USSR and ESA foresees a lander/penetrator study of the asteroid 4 Vesta, combined with the flyby of another two main-belt asteroids, and possibly a short-period comet. In addition, ESA and NASA are studying a comet nucleus sample return mission (CNSR) to a short-period comet.

Although the Giotto spacecraft suffered some damage during the P/Halley encounter, it may be redirected to P/Grigg-Skjellerup at the close approach to the earth in 1990, if the instrumentation is found to be in reasonable condition. Similar plans are under consideration for the Suisei spacecraft.

9 Meteorites

METEORITES AND INTERPLANETARY DUST

Laboratory studies of micrometeorites and results from P/Halley (Kissel et al, Nat 326, 755) provided new information about interplanetary dust particles (IDP) and the relationship between IDPs, comets and the meteorites. Reviews by Mackinnon et al (RGSP 25, 1527) and Brownlee (AREP 13, 147) show that IDPs fall into anhydrous or hydrous classes (Sandford et al, ApJ 291, 383). Some hydrated particles (Tomeoka et al, Nat 314, 338; Rietmeijer et al, LPS 15, 687) are serpentinite-rich but most are dominated by a smectite-like phase not found in carbonaceous chondrites. Anhydrous particles are distinct from chondrites, but match Halley compositional data (Brownlee et al, LPS 18, 133). Solar flare tracks (Bradley et al, Sci 226, 1432) seem to link IDPs with comets (Sandford, Ic 68, 377). Raman and IR measurements were used to compare IDPs and interstellar grains (Sandford, Sci 231, 1540; Allamandola et al, Sci 237, 56). The IDP D/H ratio is 10x terrestrial (McKeegan et al, LPS 18, 627). Large amounts of cosmic dust were found in Greenland (Maurette et al, Sci 233, 869).

CHONDRITE PETROLOGY AND COMPOSITION

Yamato 82042 is compositionally similar to CM, but with textural and petrologic affinities to CI chondrites (Grady et al, MNIP 46, 162). Compositional (Kallemeyn, MNIP 46, 151) and petrographic (Scott and Taylor, LPSC 15, C699) data indicate that Karoonda, ALH 82135, PCA 82500 and ALH 84038 are grouped. Weeks and Sears (GCA 49, 1525) and Clayton et al (LPSC 15, C245) suggested differences in chalcophiles and O-isotopes between EH3 (Prinz et al, LPS 15, 653) and higher EH types. The black chondrite in the Cumberland Falls aubrite may be unique (Verkouteren and Lipschutz, GCA 47, 1625) or a metamorphosed and reduced LL chondrite (Kallemeyn and Wasson, GCA 49, 261). Equilibrated H chondrites from the Antarctic seem compositionally different from falls (Dennison et al, Sci 319, 390) suggesting a source change 300 ka ago, a time much smaller than predicted by orbital dynamics.

DIFFERENTIATED STONY METEORITES

Magma compositions represented in How, Euc and Dio (HED) polmict breccias (Delaney et al, JGR 89, C251), ferroan eucrites (Warren and Jerde, GCA 51, 713) and IE (incompatible-element)-rich eucrites (Christophe et al, BM 110, 449) were incorporated into models explaining common eucrite basalts. Much work questioned the previously accepted position that common eucrites represent primary magmas on a ferroan body. Warren (GCA 49, 577) and Ikeda and Takeda (JGR 90, C649) suggested that common eucrites formed by fractionation of IE-poor magnesium basalt. Beckett and Stolper (LPS 18, 54) showed that the Ikeda and Takeda melt cannot produce common eucrites. Longhi and Pan (LPS 18, 570) suggested polybaric formation of eucrites. Siderophile data (Newsom, JGR 90, C613) imply that eucrites were derived from a depleted source. Delaney (LPS 17, 166) discussed two-stage igneous evolution for the HED body, consistent with Fe/Mg ratios and IE concentrations. Mittlefehldt (GCA 51, 267) showed that eucrites are more depleted in volatiles than the diogenite magma. Hewins (JGR 89, C289) reported evidence of impact melting in mesosiderites, and Wasson and Rubin (Nat 318, 168) a core-onto-crust accretional model. Brett and Keil (EPSL 81, 1) showed that aubrites were not derived from enstatite chondrites. Takeda (EPSL 81, 358) suggested that ureilites formed by partial melting of carbonaceous chondritic materials.

IRON METEORITES

New iron meteorites were classified (Malvin et al, GCA 48, 785). Variations in Re/Os ratios have implications for dating (Pernicka and Wasson, GCA 51, 1717). Group IIE meteorites were reclassified (Wasson and Wang, GCA 50, 725). New Ni and P diffusion coefficients (Doan and Goldstein, MT 17A, 1131) offer improvements in cooling-rate models. Teshima et al (GCA 50, 2073) measured Ag in phases showing different shock levels. Kracher (LPSC 15, C689) modelled the formation of IAB and IIICD meteorites by partial melting and core crystallization. Kissen et al (GCA 50, 371) found sphalerite-based pressures up to 3.5 kbar for IAB.

LUNAR METEORITES

The discovery that the Antarctic meteorite ALHA 81005 is a lunar highlands regolith breccia (Bogard et al, GRL 10, 773) and the subsequent discovery of 5 more (Yanai and Kojima, SAM 12, 17) was a boon to lunar science, and enhanced the credibility of the link between Mars and SNC meteorites. Lunar meteorites manifest shock levels similar to those of Apollo samples (Bischoff et al, MNIP 46, 21). Cosmic-ray exposure ages (Nishiizumi et al, SAM 11, 58) suggest > 2 impacts produced lunar meteorites and disparities in Mg/Fe ratios also suggest distinct sites (Warren and Kallemeyn, MNIP 46, 3). Lunar meteorites have lower IE contents than typical Apollo highlands rocks.

IMPACT STUDIES

An impact origin of the Cretaceous-Tertiary (KT) extinctions gained additional credibility with the discovery of shocked quartz (Bohor et al, Sci 224, 867; Sci 236, 705). Computer modelling provided details of the consequences (O'Keefe and Ahrens; Roddy, Hypervelocity Impact Symposium, in press); a 10-km diameter impactor produces a crater 40 km deep but ejects no mantle material. An underwater impact structure was discovered (Jansa and Pe-Piper, Nat 327, 612). The ejecta from a 90-km precambrian structure (Williams, Sci 233, 200) is preserved in sediments 300 km distant (Gostin et al, Sci 233, 198). Time-series analyses of crater ages led some (Rampino and Stothers, Nat 308, 709; Alvarez and Muller, Nat 308, 718) to suggest periodic cometary showers every 30 Ma. This hypothesis was challenged (Grieve et al, EPSL 76, 1).

IMPACT RECORD IN SEDIMENTS

Although high Ir in volcanic aerosols (Zoller et al, Sci 222, 1118) encouraged proponents of a volcanic cause for the KT extinctions, new lines of research (e.g., shocked quartz) supported the impact hypothesis (Alvarez, PT 40/7, 24). In 34 Ma of sediment (Kyte and Wasson, Sci 232, 1225) the KT Ir peak is unique in magnitude and Ir accumulation rates are inconsistent with periodic comet showers. Glass et al (JGR 90, D175) showed that the North American microtektites comprise one of two late Eocene impact horizons; Keller et al (Met 22, 25) report a third horizon. There is little evidence of major impacts at other boundaries (Orth et al, LPS 16, 631); the most promising candidate is in Jurassic sediments (Rocchia et al, JGR 91, E259). Hut et al (Nat 329, 118) reviewed the possible connection between comet showers and mass extinctions.

REFRACTORY INCLUSIONS

The formation of refractory materials in CV, CO, and CM chondrites requires multistage processes under a variety of (mainly nebular) conditions. Recent advances include discussion of fluffy, type-A (MacPherson and Grossman, GCA 48, 29), plagioclase-rich (Wark, GCA 51, 221), spinel-rich (Kornacki and and Wood, GCA 49, 1219) and fremdlinge (Armstrong et al, GCA 49, 1001) inclusions. Refractory-rich materials were found in ordinary chondrites (Bischoff and Keil, GCA 48, 693) and in interplanetary dust (Zolensky, Sci 234, 1466). Laboratory studies provided constraints on phase relationships (Mysen et al, EPSL 75, 139) and cooling rates (Stolper and Paque, GCA 50, 1785).

CHONDRULES AND MATRIX

Trace element studies of chondrules indicate precursor components rich in refractory lithophiles, common siderophiles and common lithophiles (Rubin and Wasson, GCA 51, 1923). Many primitive chondrules have fine-grained silicate rims (Scott et al, GCA 48, 1741) or coarse-grained rims (Rubin, GCA 48, 1779) that formed from fine-grained rims by sintering, probably by the chondrule-forming process. Matrix materials in ordinary and CV chondrites are roughly similar to whole-rock in composition (Grossman, LPS 16, 302). McSween (Met 20, 523) found that the O-isotopic composition of barred olivine (BO) chondrules in CV chondrites lies closer to the terrestrial fractionation line than porphyritic (P) chondrules. Coarse-grained rims are poorer in ^{16}O than their associated chondrules (Clayton et al, LPS 18, 187). Chondrule crystallization experiments demonstrate that most P chondrules were incompletely melted, in contrast to BO chondrules (Radomsky and Hewins, LPS 18, 808). As expected, many relict grains have high melting temperatures (Steele, GCA 50, 1379).

NEBULAR CONDITIONS

Chondritic meteorites indicate a hot ($T > 1300$ K) nebula (Boynton, PP II, 772), whereas astrophysical models (Morfill et al, PP II, 493) suggest that cloud collapse produced temperatures < 1000 K. High Mo and W contents of refractory inclusions (Fegley and Palme, EPSL 72, 311) suggest O_2 pressures higher than solar, but formation by evaporation (Fegley and Kornacki, EPSL 68, 181) may generate microenvironments differing from the bulk nebula. Some chondrules have been altered in high-temperature nebular episodes (Peck and Wood, GCA 51, 1503). Refractory lithophiles are fractionated only in the highly reduced EL chondrites (Kallemeyn and Wasson, GCA 50, 2153); incomplete accretion of CaS may have produced the EL fractionation (Larimer and Ganapathy, EPSL 84, 123).

PARENT BODY PROCESSES

Ordinary chondrites may originate in S-asteroids in the vicinity of the 3:1 Kirkwood gap at 2.5 AU, and carbonaceous chondrites in C asteroids in this region (Wetherill, Met 20, 1). The association of ordinary chondrites with S asteroids is disputed by Gaffey (Ic 60, 83; Ic 66, 468). Conflicting metamorphism indicators and cooling rates in ordinary chondrites suggest that asteroids were fragmented and reassembled within a few days (Grimm, JGR 90, 2022). The wide range of cooling rates in O-chondrite regolith breccias indicates breakup and reassembly after metamorphism (Taylor et al, Ic 69, 1). Petrographic evidence also indicates mixing of the ordinary asteroids (Scott et al, JGR 90, D137). Zoning in chondrule olivines supports metallographic cooling rates (Miyamoto et al, JGR 91, 12804).

METEORITES FROM MARS

Considerable circumstantial evidence supports the hypothesis that the shergottites, nakhlites, and Chassigny (SNCs) are rocks ejected from Mars (Wood and Ashwal, LPSC 12, B1359; McSween, RG 23, 391). Trapped gases in the shock-melted A 79001 shergottite resemble those in the Martian atmosphere (Bogard and Johnson, Sci 221, 651; Becker and Pepin, EPSL 69, 225); its submicroscopic relict grains rich in Fe, S, and Cl compositionally resemble Martian dust (Gooding and Muenow, GCA 50, 1049). Formation on a hydrous planet is indicated by amphiboles in Chassigny (Floran et al, GCA 42, 1213) and Shergotty (Treiman, Met 18, 409), rust in Nakhla and Lafayette (Bunch and Reid, Met 10, 303) and calcite and gypsum in A 79001 (Gooding et al, LPS 18, 345). Cratering dynamics and cosmic-ray ages suggest that SNCs were ejected from a >100 km crater ~ 200 Ma ago, followed by fragmentation 0.5 – 10 Ma ago (Vickery and Melosh, Sci 237, 738).

ISOTOPIC ANOMALIES

Isotope anomalies in meteorites show that the solar nebula was not a homogeneous, well-mixed cloud. Unequilibrated chondrites are enriched in deuterium, $\delta D \sim 250$ percent in bulk, ~ 570 percent in organic residues (Yang and Epstein, GCA 47, 2199). Heavy carbon, $\delta^{13}C \sim 140$ percent, is found in demineralized residues (Swart et al, Sci 220, 406) and extreme $\delta^{13}C$, 700 percent, in spinels (Zinner and Epstein, EPSL 84, 359). Whole rock $\delta^{15}N$ values range from -9 to +5 percent; except Bencubbin, 97 percent (Prombo and Clayton, Sci 230, 935). Oxygen isotopes are dominated by large variations in ^{16}O; refractory particles with $\delta^{18}O \sim -4$ percent were common at the CV, CO and CM locations (Clayton et al, EPSL 34, 209). Large excesses of ^{26}Mg, ^{107}Ag and ^{129}Xe reflect in situ decay of ^{26}Al, ^{107}Pd and ^{129}I, respectively (Wasserburg, PP II, 703). Mass-dependent fractionation (F) of O, Mg and Si and unknown nucleosynthetic (UN) anomalies of the neutron-rich isotopes of Ca, Ti and Cr are found in FUN inclusions. Anomalies in Sr, Ba, Nd and Sm are restricted to FUN inclusions (Papanastassiou, ApJ 308, L27; Wasserburg et al, Early Solar System, 144). Anomalies in Mg, Ca and Ti are prominent in hibonite (Hutcheon et al, LPS 14, 339; Zinner et al, ApJ 311, L103). Ne, Kr and Xe in carbonaceous residues exhibit nearly pure ^{22}Ne (Eberhardt et al, GCA 45, 1515) and excesses of the lighter and heavier isotopes of Kr and Xe (Srinivasan et al, JGR 82, 762). Diamonds inferred to be interstellar are major rare gas carriers in chondrites (Lewis et al, Nat 326, 160).

Key to the References

AA	Astronomy and Astrophysics
AAS	Astronomy and Astrophysics Supplement Series
ACM	Asteroids, Comets, Meteors (Vol II: eds Lagerkvist, Lindblad, Lundstedt, and Rickman, Uppsala University Press, 1986)
AJ	The Astronomical Journal
ApJ	The Astrophysical Journal
AREP	Annual Review of Earth and Planetary Sciences
ASR	Advances in Space Research (Vol 4: No 9; Vol 5: No 12)
ATs	Astronomicheskij Tsirkulyar
AV	Astronomicheskij Vestnik (English translations in Solar System Research)
AZh	Astronomicheskij Zhurnal (English translations in Soviet Astronomy)

AZhL	Pisma v Astronomicheskij Zhurnal (English translations in Soviet Astronomy Letters)
BAAS	Bulletin of the American Astronomical Society
BAC	Bulletin of the Astronomical Institutes of Czechoslovakia
BM	Bulletin de Minéralogie
ChAA	Chinese Astronomy and Astrophysics (English translations from Acta Astronomica Sinica and Acta Astrophysica Sinica)
CM	Celestial Mechanics
CPC	Computer Physics Communications
DANT	Doklady Akademii Nauk Tadzhikskoj SSR
EMP	Earth, Moon, and Planets
EPSL	Earth and Planetary Science Letters
ESA	European Space Agency Special Publication (most of the papers from ESA SP-250 also appear in a feature issue of Astronomy and Astrophysics)
GCA	Geochimica et Cosmochimica Acta
GRL	Geophysical Research Letters
IAUC	IAU Colloquium (No 83: Dynamics of Comets, Their Origin and Evolution, eds Carusi and Valsecchi, Reidel, Dordrecht 1985)
Ic	Icarus
IKI	Institute of Space Research, Moscow: Preprint Series
IPTI	Ioffe Physico-Technical Institute, Leningrad: Preprint Series
ISAS	Institute of Space and Astronautical Science, Tokyo: Research Notes
JGR	Journal of Geophysical Research
KFNT	Kinematika i Fizika Nebesnykh Tel (English translations in Kinematics and Physics of Celestial Bodies)
KIAM	Keldysh Institute of Applied Mathematics, Moscow: Preprint Series
KM	Komety i Meteory
KTs	Kometnyj Tsirkulyar
LPS	Lunar and Planetary Science Conference: Abstracts
LPSC	Lunar and Planetary Science Conference: Proceedings
Met	Meteoritics
MN	Monthly Notices of the Royal Astronomical Society
MNIP	Monthly Notes of the International Polar Motion Service
MPB	Minor Planet Bulletin
MSAI	Memorie della Società Astronomica Italiana
MT	Metallurgical Transactions
NASI	NATO Advanced Science Institutes Series C (Vol 156: Ices in the Solar System, eds Klinger, Benest, Dollfus, and Smoluchowski, Reidel, Dordrecht, 1984)
Nat	Nature
Obs	The Observatory
PASA	Publications of the Astronomical Society of Australia
PASJ	Publications of the Astronomical Society of Japan
PASP	Publications of the Astronomical Society of the Pacific
PP	Protostars and Planets (Vol II: eds Black and Matthews, University Arizona Press, Tucson 1985)
PSS	Planetary and Space Science
PT	Physics Today
PTRS	Philosophical Transactions of the Royal Society of London
RG	Review of Geophysics and Space Physics
SAM	Symposium on Antarctic Meteorites
Sci	Science
SSR	Space Science Reviews
VKU	*Vestnik Kharkovskogo Universiteta*

Ľ Kresák
President of the Commission