COMMISSION 15: PHYSICAL STUDY OF COMETS, MINOR PLANETS AND METEORITES (L'ETUDE PHYSIQUE DES COMETES, DES PETITES PLANETES ET DES METEORITES)

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I. INTRODUCTION

The period covered by this report, July 1987 to June 1990, witnessed a similar activity as the previous triennial interval. While the latter saw the successful encounters of several space probes with comets P/Giacobini-Zinner and P/Halley as well as the unprecedented worldwide campaigns of ground-based measurements organized by the International Halley Watch, emphasis during the 1987-1990 time period focussed mostly to the analysis of existing data, while the study of new comets continued at a slightly increased level.

There were so many international meetings organized which dealt with the subjects areas of Commission 15, that it is nearly impossible to list them here. We refer only to IAU Colloquium No. 116 on "Comets in the Post-Halley Era (CPHE)" which was held in April 1989 at Bamberg, Germany; it was attended by about 250 scientists from two dozen countries. The review papers have been edited by R. Newburn, M. Neugebauer and J. Rahe and are published by Kluwer Academic Publishers in 1990. Information on meetings relevant to Commission 15, can be found in the IAU Information Bulletins or in the Astronomy and Astrophysics Abstracts.

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II. COMETS : CLAUDE ARPIGNY

1. COMETARY NUCLEI

The first pictures of a resolved cometary nucleus, P/Halley's acquired by spacecraft flybys in 1986, continued to play an essential role in the study of cometary nuclei, especially when linked with new information about the gas and dust production of this comet. Fundamental questions such as those pertaining to the porosity and bulk density of the nucleus, or to its detailed chemical composition and near-surface differentiation, were addressed. Reviews dealing with cometary nuclei in general were written by Whipple (AA 187, 852), by Keller (ESA 278, 447; PCC chap. 2) with some emphasis on the Halley nucleus, and by A'Hearn (AREP 16, 273) from an observational point of view. Modelling aspects were reviewed by Möhlmann and Kührt (ASR 9, 17) and Colangeli et al. (ESA 302, 17), relationships between cometary nuclei and asteroids were reviewed by Weissman et al (A II, 880).

The spacecraft data on the size, shape, and surface temperature of P/Halley's nucleus were compared with the theory previously developed e.g., by Shulman ("Nuclei of Comets", Moscow: Nauka 1987-in Russian). As predicted, not only has the comet a monolithic, black, hot nucleus, but its calculated surface temperature (422 K at r=0.8 AU) also fits the measured one (420 +/- 60 K) rather well.

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Radar detections and observations involving simultaneous IR radiometry and visual photometry were carried out for a number of comets; analyses bearing on size, shape, spin period, albedo, and temperature were published for comets IRAS-Araki-Alcock (Sekanina, AJ 95, 1876), P/Neujmin 1 (Campins et al, ApJ 316, 847), P/Arend-Rigaux (Veeder et al, AJ 94, 169; Millis et al, ApJ 324, 1194) and P/Tempel 2 (A'Hearn et al, ApJ 347, 1155). Some differences are found between different comets, but more striking are the similarities.

Size, Mass and Density

Although the size and shape of P/Halley, as approximated by an ellipsoid of semiaxes 8x4x4 km, are closely shared by several other comets, i.e., IRAS-Araki-Alcock and probably P/Tempel 2 and P/Arend-Rigaux, the size distribution extends over a wide range. "Asteroid" 2060 Chiron, which was found to have the physical/chemical nature of a comet (Hartmann et al, Ic 83, 1; Meech and Belton, and Luu and Jewitt, AJ, in press), has a radius of about 100 km. On the other hand, assuming a low albedo of 0.04, rather small radii (1 to 2.5 km) were derived for several comets (Luu and Jewitt, BAAS 20, 835, Ic 86, 69; Sekanina, AJ 95, 911, AJ 98, 2322, AJ 99, 1268). Upper limits from IR radiometry are 3 km for P/Encke (Campins, Ic 73, 508) and about 0.4 km for comet Sugano-Saigusa-Fujikawa (Hanner et al, AJ 94, 1081). Bailey (BDM, 7) discussed the mass distribution of comets in relation to the galactic context. The mass and density of P/Halley continue to stimulate debate. Depending on the adopted gas production curve, values from 0.3 g/cm^3 (Rickman, ASR 9, 59) to 0.6 g/cm^3 (Sagdeev et al, Nat 331, 240) are obtained from nongravitational perturbations. However, Peale (Ic 82, 36) and Yeomans and Wimberly (BAAS 21, 923) argue that the density is undetermined owing to a number of modelling uncertainties. A somewhat less model-dependent analysis based on OH-line data (Colom et al, ACM, 293) indicates 0.4 g/cm^3. Using an extensive sample of short-period comets, Rickman et al (ESA 278, 471) estimate a typical density below 0.5 g/cm^3. P/Tempel 2 with a relatively fast spin might be unstable unless its density exceeds 0.3 g/cm^3 (Jewitt and Luu, AJ 97, 1766).

Shape and Spin

Belton (CPHE) presents a critical review of the techniques used to characterize the rotation state of cometary nuclei, from both the observational and theoretical points of view. The spin state of P/Halley is still an unresolved issue. Support for a period near 7 days was found by various means (Stewart, AA 187, 369; Festou et al, AA 187, 575; Beisser, EMP 48, 127; Hoban et al, AA 195, 331; Colom and Gérard, AA 204, 327; Schultz and Schlosser, AA 214, 375; Watanabe, ATAO, 1). Modelling in terms of free precession of an asymmetric rotator involves a complex range of possibilities, and quite different configurations appear from different analyses, as seen from comparison of recent works (Abergel et al, AG 7, 129; Sagdeev et al, AJ 97, 546; Möhlmann, AN 310, 151; Belton, Ic 86, 30). Modelling in terms of forced precession involving the jet torque of localized outgassing (Peale and Lissauer, Ic 79, 396) indicates a preference for precession about the shortest axis. Sekanina (ESA 278, 315) devised a method of using the orientations of fan-shaped comas as indicators of spin axis orientation for comets with active regions concentrated near the poles. By applying this method he found a slow forced precession of the spin axis of P/Encke (AJ 96, 1455) and quick precession for P/Schwassmann-Wachmann 3 during Earth approach in 1930 (AJ 98, 2322). He also treated P/Tempel 2 (ESA 278, 323, IAUC 4624) and IRAS-Araki-Alcock (AJ 95, 1876). Not unexpectedly, high axial obliquities are common. Spin periods (Watanabe and Abe, EMP 44, 141; Jewitt and Luu, AJ 97, 1766; Wisniewski, Ic 86, 52; and references above) range from 9 hours to several days. For giant comet Chiron a period of only 5.9 hours has been observed (Bus et al, Ic 77, 223). Elongated shapes with axial ratios near 2:1:1 appear common, and a similarity with the shapes of Trojan asteroids (Hartmann et al, Ic 73, 487; Jewitt and Meech, ApJ 328, 974) may indicate a genetic relation. These bodies also appear spectrally similar (Jewitt and Luu, AJ, in press).

Surface Material and Topography

Refined analysis of Giotto images allowed the identification of a number of surface features of dimensions 0.5-1 km (Keller et al, Nat 331, 227; Reitsema et al, ASR 9, 81), foremost among which are the 'crater' and the 'mountain'. A review of Vega data on surface structures is given by Merényi et al (Ic 86 9). Radar observations of comet IRAS-Araki-Alcock (Harmon et al, ApJ 338, 1071) indicate a surface which is moderately porous and very rough on meter-scale or more. For P/Halley (Campbell et al, ApJ 338, 1094) the nucleus was not detected, implying a high porosity. Surface temperatures on P/Halley have proved very high, based on Vega IKS data (Emerich et al, AA 187, 839). Similar conclusions appear from IR measurements on other comets. These high temperatures correspond to a very dark surface material, and typical values of the visual albedo are 0.02-0.04. The colors range from quasi-neutral to very red.

Activity Level and Distribution

Several discrete outgassing areas have been identified on the P/Halley nucleus from Giotto imagery (Reitsema et al, ESA 278, 455) and from DUCMA dust impact rates (Rabinowitz, AA 200, 225); they seem to behave differently depending on their distance from the pole (Reitsema et al, Sci 243, 198). A review of evidence for localized outgassing is given by Sekanina (CPHE). The active fraction of the surface seems even smaller for most other well-studied comets than for P/Halley, ranging upward from about 0.1%. This evidence comes from observed gas production rates and indicates that most nuclei are almost completely deactivated by a non-volatile surface layer, reaching very high temperatures as observed. In many cases it appears that the dominant active spots are situated near the poles.

Physical Processes

Modelling of the response of a cometary nucleus to solar heating, including crystallization, gas release, and related phenomena (Prialnik and Bar-Nun, ApJ 313, 893, Ic 74, 272; Espinasse et al, Ic, in press) leads to a picture of a crystalline crust with upward-diffusing gases overlying an amorphous interior. Calculations for specific comets include P/Tempel 1 (Bar-Nun et al, Ic 79, 116) and P/Churyumov-Gerasimenko (Espinasse et al, ESA 302, 185). A simple model attempting to explain the behavior of P/Schwassmann-Wachmann 1 by local, sporadic crystallization was proposed by Jewitt (ApJ 351, 277). Near-surface differentiation and its influence on gas production curves has also been modelled without regard to crystallization (Fanale and Salvail, Ic 72, 535, Ic 84, 403; Mekler et al, ApJ 356, 682). Gas flow in the porous material with accompanying recondensation and transport of latent heat has been recognized as an important process, also in view of experimental results (Spohn et al, ASR 9, 127). The properties of dust mantles were discussed by Smoluchowski (AJ 97, 241) and modelling based on simple concepts (Rickman et al, AA, in press) showed them to occur ubiquitously on short-period comets. Further thermal modelling efforts involve steady-state internal temperatures (Herman and Weissman, Ic 69, 314), the development of topography (Colwell et al, Ic 85, 205), and seasonal effects on comet Halley (Weissman, AA 187, 873), treated in particular for a precessing nucleus (Banaszkiewicz and Szutowicz, ACM, 239).

Darakhshan (KFNT 6, 28) obtained an analytical solution for the surface temperature of a rotating ellipsoidal comet nucleus and computed the distribution of temperature on the surface of some comet nuclei. In their numerical model Marov et al (AV 19, 47) evaluated the reaction force on the nucleus. A proposal to explain the discrepancy between P/Halley's measured and calculated gas release was made by Drobyshevsky (EMP 43, 87), who supposed that there should be combustion of products of electrolyzed water ice. Shulman (KTs 414) showed that the gas production of P/Halley's nucleus could be enhanced by a factor of about 3 if the crater structure of its dust crust be taken into consideration. Laboratory simulations of surface phenomena on cometary nuclei were performed in Germany (Kochan et al, ASR 9, 113; Gruen et al, CPHE), and in the USSR (Ibadinov, ASR 9, 97; Ibadinov et al, CPHE). They showed the buildup of nonvolatile mantles (Thiel et al, ESA 302, 221), confirmed Shulman's conclusion (l.c.) that the temperature difference between the outer surface of the nucleus dust crust and the dust-ice border did not depend on the thickness of the crust (Ibadinov and Rakhmonov, KTs 395), suggested their thermal mechanical properties (Ibadinov et al, ESA 278, 713; Kochan et al, ESA 302, 115) and identified possible mechanisms of dust emission related to such crusts (Gruen et al, ASR 9, 133; Kohl et al, ESA 302, 201). The evolution of ice mixtures was reviewed by Klinger (CPHE). Gas trapping in amorphous H_2O ice (Bar-Nun et al, PR B38, 7749) is now an influential concept and may account for a subsurface source of volatiles at the level of crystallization (Schmitt and Klinger, ESA 278, 613; Schmitt et al, ESA 302, 65).

Chemical Composition and Structure

The composition of cometary nuclei was reviewed by Delsemme (ESA 278, 19, PTRS A325, 509) and Brownlee (ESA 302, 233). Reviews with special emphasis on the volatile composition were given by Weaver (HA, 387) and Krankowsky and Eberhardt (HWWI), on the refractory composition by Jessberger et al (OPSA, 167), and on the dust-to-gas ratio by Keller (ESA 302, 39). The mode of coexistence of water ice and more volatile species particularly attracted attention in view of its importance for concluding about comet origins from observed compositions. Clathrate hydrates were thus considered by Lunine (BAAS 19, 887) and Engel et al (Ic 85, 380), and their role in shaping the microporous structure was discussed by Smoluchowski (MN 235, 343). Arguments against clathrates were summarized by Klinger (ESA 302, 55) and a review of different related models was given by Schmitt et al (ECDA, 259).

The structure of cometary nuclei can be modelled as a random agglomeration of ice-coated interstellar grains (Greenberg and Hage, ESA 302, 47, ApJ, in press). This should be porous and fractal in geometrical nature (Meakin and Donn, ApJ 329, L39; Donn and Meakin, LPSC 19, 577; Donn, CPHE and AA, in press).

2. COMETARY GASES

Theoretical Models

The development of models of molecular excitation was stimulated by the availability of new good observational data and the detection of new species. Infrared and microwave emission of H_2O, including radiative transfer, was modelled and applied to P/Halley infrared observations (Bockelé-Morvan, AA 181, 169; Bockelé-Morvan and Crovisier, AA 187, 85; AA 216, 278). From laboratory measurements, Crovisier (AA 213, 459) reevaluated H_2O photodissociation. H_2CO IR fluorescence was modelled by Brooke et al (ApJ 336, 971) and Reuter et al (ApJ 341, 1045). Krishna Swamy and Wallis (AAS 74, 227) studied the fluorescence of S_2. Radicals were also studied: OH (Schleicher and A'Hearn, ApJ 331, 1058); CS (Prisant and Jackson, AA 187, 489); NH (Kim et al, Ic 77, 98) and NH_2 (Tegler and Wyckoff, ApJ 343, 445), with discussions on the NH_3 abundance; C_2, for which probabilities of the singlet-triplet transitions are now available from the theory (Krishna-Swamy and O'Dell, ApJ 317, 543; O'Dell et al, ApJ 334, 476; Gredel et al, ApJ 338, 1047; Lambert et al, ApJ 353, 640). Further progress in this area depends upon laboratory work, especially for ions and radicals (band strengths, collision cross-sections, photodissociation rates and branching ratios).

Many efforts were devoted to the physico-chemistry of the coma. Monte Carlo simulations were performed in order to study the hydrogen distribution and its coupling with other species, to interpret Lyman alpha observations, to evaluate photolytic heating of the coma, and to study the transition from the collisional coma to the exosphere (Combi and Smith, ApJ 327, 1026 and 1044; Bockelé-Morvan and Crovisier, ESA 278, 235; Ip, ApJ 346, 475; Hodges, Ic 83, 410). Water recondensation and clusters were studied in detail by Crifo (Ic 84, 414). Sophisticated chemical models, some of them including plasma and solar wind interactions, continued to be developed (Allen et al, AA 187, 502; Wegmann et al, AA 187, 411; Schmidt et al, CPC 49, 17). Several models now address the more realistic case of a non-stationary, non-isotropic coma (Komle and Ip, AA 187, 405; Kitamura, Ic 72, 555; Korosmezey and Gombosi, Ic 84, 118). Contributions to the study of gas dynamics in comets were made by Bisikalo and Shematovich (ATs 1488, 1) who also developed a more realistic numerical model for the inner coma, taking into consideration the effect of the ice grains sublimation as well as of the IR radiation transfer. A delicate aspect of comet gas dynamics is the problem of the near-wall (Knudsen) layer. Bisikalo et al (ASR, 53) showed how the near-wall outflowing gas relaxed there from the initial temperature anisotropy to the equilibrium velocity distribution. Marov et al (IAM 66) presented a model of the dust-gas atmosphere that can be used to analyze the surface photometry data. Detailed critical reviews of many of these models were presented by Crifo (ASR, 197; CPHE) and Huebner et al (CPHE). Although most of the individual physical processes seem to be now well understood, a "grand design model," which would incorporate all of them simultaneously, is still to be elaborated.

Observations

The spectral signatures of OH were observed and analyzed in several recent comets: in the UV with the IUE (Roettger et al, Ic 80, 303), from the Vega spacecraft (Parisot et al, ESA 278, 255) or from the ground (Festou et al, AA 227, 609); in the 18-cm radio lines at Nancay, at Green Bank and with the VLA (Gérard et al, AAS 74, 485, AAS 77, 379, ACM, 317; Schloerb, ACM, 427; Palmer et al, AJ 97, 1791). Temporal variations were studied in connection with possible outbursts (Silva and Mirabel, AA 201, 350) and nucleus rotation (Colom and Gérard, AA 204, 327). A systematic study of OH and other radio line shapes lead to the determination of the coma expansion velocity and its evolution with heliocentric distance and gas production rate (Bockelé-Morvan et al, AA, in press; Combi, Ic 81, 41; Tacconi-Garman et al, ACM, 455), in agreement with hydrodynamical models. Although the matter is not yet completely settled, significant progress was made in reconciling gas production rates determinations from UV and radio OH observations, by developing a realistic model of collisional quenching of the OH maser (Schloerb, ApJ 332, 524, ACM III 431; Gérard, AA 230, 489).

Many spectrophotometric studies of the cometary radicals were published. In particular, pursuing their systematic observing programs, Cochran et al (Ic 79, 125), Cochran (ACM, 283) and Newburn and Spinrad (AJ 97, 552) determined radical production rates for many comets. Narrow-band-filter photometry is also an important tool to derive homogeneous sets of such data, and the publication (Osborn et al, Ic, in press) of detailed standard stars measurements in the cometary system recommended by the IAU will be a very useful reference.

Filonenko and Churyumov (KTs 413) found discontinuities in the absolute brightness and photometric parameters of comet Halley. Nazarchuk (KTs 372 and 377) analyzed the spectra of comet Halley obtained with the 6-m telescope at spectral resolution of about 2 A, spatial resolution of about 2500 km, and time resolution of about 5 min. She found interesting features and effects: the luminescence of short-lived dust particles (probably the CHON grains), the sodium D-lines with anomalous intensity ratio, the Balmer emissions of atomic hydrogen, and short-term variations of the intensities of the main comet emissions. Wyckoff et al (ApJ 325, 927) obtained abundances for CN, CH, NH_2 in P/Halley at the time of the space probe encounters. Peculiar spectral profiles of the OH and CN emissions in this comet observed from Vega 2 were interpreted as possible signatures of the photodissociation of organic molecules (Clairemidi and Moreels, ESA 302, 177). The spatial structure of the CN emission was studied in terms of jets (Hoban et al, AA 195, 331; Cosmovici et al, Nat 332, 705) and shells (Schulz and Schlosser, AA 214, 375). Nonstationary ring structures in the tail of P/Halley were studied by Churyumov (CPHE) and in the head of P/Stefan-Oterma by Tarashchuk and Dyakonova (KTs 375). OH and NH jets in P/Halley were described by Clairemidi et al (AA 231, 235).

High-resolution spectra of OI and NH_2 in P/Halley were analyzed by Debi Prasad et al (PASP 100, 702), Smith and Schempp (Ic 82, 61), Magee-Sauer et al (Ic 76, 89; Ic 84, 154), Kerr et al (ASR 9, 181). Detection of a Greenstein effect in the OI 1302 A emission of the same comet led Dymond et al (ApJ 338, 1115) to an estimate of 2.2 km s^{-1} for the mean outflow velocity of the oxygen atoms. Measuring differential Doppler shifts across the coma of P/Halley with respect to its nucleus, Herbig (AJ 99, 1262) found relative velocities reaching 3-4 km s^{-1} at 10^4 km. NH and NH_2 were studied by Cochran and Cochran (ACM, 289), Schleicher and Millis (ApJ 339, 1107) and Magee-Sauer et al (Ic 82, 50). Churyumov reported detection of visual emissions of neutral CO in the spectra of comet Skorichenko-George, where Asundi's bands (5746-6160 A) and the triplet bands (4437-6037 A) seemed to be present.

Decisive progress was made in the identification and abundance evaluation of several possible parent molecules by modelling the mass spectrometer results of Giotto in Halley's coma. From ion composition measurements, Allen et al (AA 187, 502) estimated CH_4 and NH_3 gas production rates of 0.02 and 0.01-0.02, respectively, relative to H_2O. The presence of HCN, H_2S and polymerized formaldehyde was also inferred (see section on cometary dust). More direct information was obtained from IR and microwave spectroscopy: an analysis of the 1.38-micrometer water band observed from Vega was published by Krasnopolsky et al (AA 203, 175). Following its detection in P/Halley, the 2.7-micrometer water band was observed by FTS from stratospheric airplane in comet Wilson (Larson et al, ApJ 338, 1106). Detailed examination of P/Halley interferograms obtained in March 1986 revealed two H_2O outbursts (Larson et al, Ic 86, 129). IR observations of CH_4 place low upper limits (0.005 to 0.02) on its abundance in comets P/Halley and Wilson (Drapatz et al, AA 187, 497; Kawara et al, AA 207, 174; Larson et al, ApJ 338, 1106). H_2CO, identified at 3.6 micrometers in the Vega spectrum of P/Halley (Combes et al, Ic 76, 404; Mumma and Reuter, ApJ 344, 940), was detected in the same comet and in Machholz (1988j) at 6-cm wavelength with the VLA (Snyder et al, AJ 97, 246; Ic 86, 289), and at millimeter wavelengths in Austin and possibly P/Brorsen-Metcalf (IAUC 4851 and 5020). Radio spectroscopy proved very efficient for the study of cometary parent molecules with the recent observations of comet Austin where the new species H_2S and CH_3OH possibly were detected (IAUC 5022 and 5027).

It is still unclear to which extent the observed stable species come from the nucleus, or from a distributed source, such as grains, or more complex molecules. It seems now established that most of the CO does not come from the nucleus, but the question is still debated for other species, like HCN. This point is critical for the derivation of reliable production rates. It must also be realized that the observed gas phase abundances may greatly differ from molecular abundances within the nucleus, because of fractionation during the sublimation process.

3. COMETARY DUST

Physical/Chemical Characteristics

The present state of knowledge regarding the nature of the cometary particulates was summarized by McDonnell et al (CPHE), who intercompared and combined the data from in situ measurements made during the comet encounters (mass and size distributions, density and chemical nature) with the results derived from remote optical observations (color, albedo, polarization curves and emission features). These authors stressed the complexity of the cometary dust properties and pointed out a number of remaining ambiguities or important unanswered questions. The various characteristics of the cometary solid particles were reviewed, with special emphasis on their relationships with the interplanetary dust or with the interstellar grains, by Brownlee (HA, 281), Dollfus (HA, 295), and Greenberg (HA, 241).

The chemical composition of cometary dust was studied extensively (e.g., Langevin et al, AA 187, 761; Jessberger et al, Nat. 332, 691; Lawler et al, Ic 80, 225).

Further analyses of the in situ time-of-flight impact-ionization mass spectrometers provided significant data, showing in particular that Halley's dust is composed of two end-member compositions (CHON and SILICATE) (Jessberger, CPHE). The mineral grains are heavier than the organic ones and are seen closer to the nucleus (Clark et al, AA 187, 779; Hsiung and Kissel, ESA 278, 355). None of the detected particles are single mineral grains (Jessberger et al, Nat 332, 691, Lawler et al, Ic 80, 225). Furthermore, most Mg appears to be contained in silicates, whereas Fe is found in a range of materials such as metal, magnetite, sulfides, and silicates. It is concluded by Jessberger (CPHE) that within a factor of two, the abundances of the rock forming elements are the same as in the whole Solar System, but the CHON elements are more abundant than in CI-chondrites and approach the Solar System abundances. This evidence suggests that the mineral grains in Halley's dust are likely to represent pristine material from the early Solar System, as noted by Sekanina (AA 187, 789) and Greenberg (EID, 383). Isotopic abundances for O, Mg, S, Cl and Fe are near to the terrestrial values (Solc et al, ESA 278, 359; Vanysek, CPHE), but high (90-5000) intensity ratios 12/13 are real $12^c/13^c$ ratios (Jessberger, CPHE) and this might suggest the existence of interstellar grains in the comet or result from ion-molecule reactions.

Information regarding the presence of some "parent" molecules probably associated with P/Halley's particulates was derived from mass spectrometric data. For example, mass peaks attributed to H_2CN+ and to H_3S+ suggested the presence of HCN and H_2S, respectively (Ip et al, AG 8, 319; Marconi et al, ApJ 352, L179). Similarly, a series of peaks was interpreted as due to successive dissociation of polyoxymethylene (POM) by Huebner et al (ApJ 320, L149) and by Mitchell et al (Sci 237, 626). The CHON particles might thus constitute an extended source for these molecules as well as for some of the observed CO, for H_2CO and for the parents of some radicals such as CN or C_2 seen in jets (see, however, the critical remarks on this problem in Krankowsky and Eberhardt, HWWI). The production of radicals from CHON grains in jets was also discussed by Combi (Ic 71, 178) and by Ip (ASR).

The analysis of the IR spectra of comets also yields some clues on the nature of their dust component (Campins and Tokunaga, NASA, 1; Crovisier, ESA 290, 15; Encrenaz and Knacke, CPHE; Krishna Swamy et al, ApJ 340, 537; Tokunaga and Brooke, Ic 86, 208). The emission at 3.2-3.6 micrometer, first detected in P/Halley, was seen in four other comets: Wilson (Allen and Wickramasinghe, Nat. 329, 615; Brooke et al, ApJ 336, 971), Bradfield (Brooke et al, Ic 83, 434), P/Brorsen-Metcalf (Bregman et al, BAAS 21, 1155; Brooke et al, BAAS 21, 993) and Austin (IAUC 5012). Gehrz et al (Ic 80, 280), however, reported no evidence of the 3.4 micrometer feature in P/Encke. Although it is known that this emission is characteristic of C-H stretching in hydrocarbons, its actual origin in cometary spectra is still open to discussion (Chyba et al, Ic 79, 262; Colangeli et al, Ic 86, 198; Combes et al, Ic 76, 404; Encrenaz et al, AA 207, 162; Grigoriev, KI 25, 810; Knacke (ISD, 415); Krishna Swamy et al, Ic 75, 351). It is very likely that an important contribution is due to thermal emission by carbonaceous small grains or to UV pumped fluorescence of such grains or of large molecules, but resonance fluorescence of hydrocarbon molecules may play a role. It is clear that more specific identifications will require further, higher-resolution IR spectroscopic observations. The latter should also provide some insight into the relationship between the cometary emitters and the carbonaceous chondritic material, interstellar grains, and laboratory carbonaceous materials showing similar 3.4 micrometer emission features. Some structure in the broad 10-micrometer emission (one sharp peak at 11.3 micrometers) discovered in P/Halley by Bregman et al (AA 187, 616) was observed also in other spectra of this comet (Bouchet et al, AA 174, 288; Combes et al, Ic 76, 404; Campins and Ryan ApJ, 341, 1059) and in comet Bradfield (Hanner et al, ApJ 348, 312), in contrast to no feature in comet Wilson (Lynch et al, Ic 82, 379). The 11.3 micrometer peak seems to be due to crystalline olivine, as first noted by Bregman et al.

Mass Distribution

Some knowledge of the mass distribution of the cometary dust was derived mainly from the in situ measurements of P/Halley (e.g., McDonnell et al, ASR 9, 277; CPHE). Extremely small grains (10^{-19} kg) appeared unexpectedly; they played an ineffective role in light scattering and thermal emission (Hanner et al, AA 187, 653), and in total mass of ejected grains (Gruen et al, ESA 278, 305). However, their role should be examined in more detail in future work, e.g., as the second source of gas in the coma (Lamy and Perrin, Ic 76, 100; Keller et al, AA 227, L1), a progenitor in the origin of life (Clark, CPHE), and a link between large molecules and dust grains.

Dust/Gas Mass Ratio

On the other hand, the "anomalous" excess of large grains in the mass range 1 microgram to 1 milligram plays a key role in a determination of the dust to gas mass ratio ejected from the cometary nucleus (Gruen et al, ESA 278, 379). Taking account of the observed mass excess in the coma, the ratio is estimated to be 1.5 (Gruen et al, ESA 278, 305) and 2 (McDonnell et al, CPHE). Crifo (ESA 278, 399) gives a value of 2.5, from a comparison of the dust size distribution expected from dust hydrodynamics in the coma with that from optical observations. Assuming (C/Mg) dust+gas=solar, Jessberger (CPHE) sets the ratio at 2.7. The existence of large grains (1-50 mg range) was confirmed from sudden changes of the viewing direction of the Halley Multicolour Camera (HMC) (Curdt and Keller, Ic 86, 305). These large grains are ejected from the cometary nucleus with low relative velocity (Crifo ESA 278, 399; Cremonese and Fulle, Ic 80, 267; Banaszkiewicz et al, CPHE), and consequently they stay for a fairly long time along the orbit of the parent comet (Mukai et al, Ic 80, 254). On the basis of a systematic analysis of IRAS data, Sykes (ApJ 334, L55; CPHE) found 64 different dust trails consisting of large grains extending both ahead and behind the comet.

Dust-Gas Interaction and Dust Dynamics

P/Halley's highly anisotropic and localized activity revealed by the Giotto HMC images emphasized even more strongly the need for a description of the ejection of matter by a cometary nucleus in terms of jet-like structures emanating from limited areas. Simple cone ejection models were used to interpret the intensity profiles in "jets" observed in the vicinity of comet Halley's nucleus, invoking purely geometrical effects (Huebner et al, Ic 76, 78) or with an additional particle fragmentation effect (Thomas and Keller, AG 8, 147). Comparison with models of axisymmetric jets provided some information on the emitting sources and on the coupling between the dust and the gas (Reitsema et al, Ic 81, 31). Rather elaborate models based on a time-dependent treatment of the inner coma dusty gas dynamics were developed by Kitamura (Ic 72, 555; 86, 455) and by Körösmezey and Gombosi (Ic 84, 118), who were able to study the formation and evolution of axisymmetric jets and to predict some of their properties, such as the possibility of shock formation between interacting jets or the formation of a subsolar dust spike and of a jet cone.

Dynamical analysis of IRAS images of P/Tempel 2 indicated the existence of rather large (mm-sized and larger) particles in the outer coma (Campins et al, Ic 86, 228) and in the dust trail of this comet (Sykes et al, Ic 86, 236). The Finson-Probstein theory was applied by Birkett (MN 235, 497) to explain the structure of P/Halley's dust tail and to derive the grain size distribution; this work suggested the presence of very small (submicron) particles on hyperbolic orbits and showed that only grains larger than about 10 micrometers contributed to the zodiacal cloud. A major contribution to this cloud by short-period comets, in particular by P/Encke, was inferred from a study of the dynamics of interplanetary dust (Gustafson et al, Ic 72, 568 and 582).

Variability of Dust Properties

Variations in dust characteristics were observed rather early in comet researches. Newburn and Spinrad (AJ 97, 552) found a large variation of the dust production rate in 18 different comets. The absence of a correlation between the color and the sun-comet distance was noted in 23 comets by Jewitt and Meech (AJ 96, 1723). The use of 2D detector arrays in comet observations brought about several new aspects in the study of the dust coma, in P/Halley, such as a steeper decrease of radial brightness in JHK colors and the bluest colors at the photocenter (Campins et al, Ic 78, 54), an increase in albedo away from the nucleus (Hammel et al, AA 187, 665), and a maximum polarization in dust jets (Eaton et al, Ic 76, 270). 2D color maps of the dust coma were also obtained in Halley by Hoban et al (Ic 79, 145). This evidence strongly suggests that the changes in dust properties occur while the grains are traveling in the coma; theu can be explained by radiation pressure. The fragmentation of large conglomerates of particles in the coma was proposed by Simpson et al (ASR, 259; ESA 278, 391) from their detection of a rapid increase in dust fluxes within a short time interval (+/- 10 s). They referred to "clusters of particles or dust packets" consisting of low mass particles (ab. 10^{-16} kg). As for fragmentation mechanisms, electrostatic forces (Boehnhardt and Fechtig, AA 187, 824) and evaporation of CHON grains (Wallis et al, ASR 213; Lamy and Perrin, Ic 76, 100) were proposed, but this is still an unsolved problem.

Temporal variations in dust properties, associated mainly with jets or bursts, were observed. In comet Halley, the linear polarization increased during outbursts (Kikuchi et al, AA 187, 689) and J-H colors became bluer at maximum brightness (Campins and Tokunaga, NASA CP-3004, 1). One reason might be an enhancement of the number of small grains during the outbursts (Mukai et al, ESA 278, 427).

4. COMETARY PLASMA

This section will concentrate on advances in the understanding of cometary plasmas, primarily in the context of remote (optical) observations as supplemented by theoretical work. It will spend less time on studies of plasma/field data conducted by the Halley encounter teams; such efforts have concentrated on mass-loading of the solar wind, magnetic wave properties and turbulence, energy spectra of the loaded solar wind, etc. This literature has become so large and specialized that it is beyond the scope of this brief review. A current treatment of these topics is to be found in the Proceedings of the Chapman Conference on Cometary Plasmas (AGU). It is clear that the data on comet P/Halley returned by hundreds of observers worldwide (many participating in the IHW program) were so voluminous and of such high quality that we have only "scratched the surface" in their interpretation. Much work remains to be done, and the imminent release of the IHW Archive promises a new era of increased understanding as many of the most useful datasets become generally available to researchers for the first time.
Ip (1987; in Magnetotail Physics, ed. A. Lui, p. 367) gives a very thorough review of cometary plasma tails that addresses a number of important aspects: interpretation of in situ spacecraft results and of remote observations, the relationships between ground and space data, and theoretical modelling. Mendis et al (AG 7, 99) review the various plasma/field boundary surfaces in comet Halley revealed by the space probes. Jockers (AGU) presents a lengthy discussion of coma and tail ions, with special emphasis on large-scale structures (tail rays, disconnection events, kinks) and their interpretation. Brandt and Niedner (AA 187, 281) take a similarly observational approach to much of the same kinds of data as Jockers, but draw rather different interpretations, namely in the area of DEs (see discussion on tail ions below).

Modelling

Schmidt-Voigt (AA 210, 433) used a 3D numerical simulation scheme to examine the time-dependent effects in the response of bright comets to 180-degree reversals and

90-degree rotations of the interplanetary magnetic field (IMF). Because no obvious disconnection effects were seen in the model for the 180-degree case, Schmidt-Voigt questions the applicability of the frontside magnetic reconnection model of disconnection events (DEs) developed by Niedner and Brandt (ApJ 223, 655). In contrast, the author does see possible effects in the 90-degree field rotation scenario and proposes this as a more likely generator of DEs. Niedner then asks: why do we see an extremely high clustering of DEs around the times of sector boundaries? Ogino et al. (JGR 93, 9568), who in earlier papers have appeared to generate DEs in computer simulations of sector boundary interactions with comets, used 3D time-dependent MHD simulations to examine the structure of comet P/Halley during the times of the Halley space probes encounters. Correctly reproduced by their model was a weak bowshock at 3.2E5 km in front of the comet, a maximum magnetic field strength in the barrier region enhanced some 6-8X over interplanetary values, and a plasma tail consisting of cold plasma oriented normal to the original IMF direction. Körösmezey et al (JGR 92, 7331) used numerical techniques to solve spherically-symmetric and time-dependent continuity, momentum, and energy equations in a Halley-like cometary ionosphere at 1 AU. The main result was the confirmation of a steeply-increasing electron temperature with distance from the nucleus (beyond the region where electron- neutral collisions are abundant). The simulation also showed the transition of plasma outflow from supersonic to subsonic velocities within the ionosphere, but the existence of an inner shock was not firmly established.

Coma Ions

Ip, Spinrad, and McCarthy (AA 206, 129) examined narrow-band CCD H_2O+ images of Halley taken 13 hours after the Giotto encounter and found a density maximum of water ions 2.E4 km upstream of the nucleus. This concentration closely matches that seen in situ by Giotto (and days earlier by Vega), leading to speculation that such features are spatial (i.e., quasi- stationary) and not temporal in nature. DiSanti, Fink, and Schultz (Ic 86, 152) analyzed H_2O+ CCD images of Halley's coma, supplemented by spectroscopic data, around the time of Vega-1's flyby of the comet. They were able to obtain several points of agreement with the in situ data, such as the size of the collision zone, the central depletion of ions, and the $1/R^2$ fall-off of number density. Acceleration of ions with distance from the nucleus was calculated to be in the 100 cm s^{-2} range. Prasad et al (J. Astrophys. Astr. 10, 1) observed a transient H_2O+ event in Halley's coma on 1986 March 13.0 UT, which they describe as a complex detached blob with internal relative velocities of order 35 km s^{-1}. They attribute the formation of this structure to the comet's encounter with a magnetic sector boundary (Niedner and Brandt, ref. above). In their laboratory experiments, Khashimov and Shoyekubov (DANT 32, 22) studied the formation of molecular ions. High-velocity collisional interaction between cometary and zodiacal dust particles was proposed as a possible mechanism for the formation of heavy ions in a cometary atmosphere and for the generation of hot plasma and X-rays there (Ibadov, ATs 1531, 27; 1499, 5).

Tail Ions

Ip (ApJ 353, 290) showed that thermalization of energetic neutral atoms created by charge-exchange recombination in the coma of P/Halley could explain the production of energetic cometary ions at large distances from the nucleus; his simplified model, however, failed to reproduce the flux of hot ions detected near the magnetic-field free cavity.

Fabry-Perot H_2O+ spectra of P/Halley taken at several distances from the center of the comet out to 2.E6 km by Scherb et al (Ic 86, 172) showed that the acceleration of the ions varied from night to night, covering the range 30 - 300 cm s^{-2}; unusual kinematic behavior on some nights could be related to DEs. Kochhar and Trehan (MN 234, 123) gave a Kelvin-Helmholtz instability treatment of waves observed in comets Morehouse and Kohoutek and found, generally, that an increase in the helicity for any given wavelength tends to decrease the instability growth rates. Kotsarenko et al (KTs 402) explained the occurrence of wave structures in the tail of P/Halley as a special case of the Kelvin-Helmholtz instability. They showed why waves were observed rather than hydromagnetic noise with a wide spectrum of wave numbers and random phases. The conditions for the onset of a streaming instability between the solar wind and cometary dust were determined by Havnes (AA 193, 309) who concluded that such an instability required rather low neutral gas densities and was not likely to be a common phenomenon in the inner Solar System. Lynch and Russell (PASP 100, 1122) obtained IR brightness measurements (2.3-10.3 micrometer) of Halley in the 1985 November 8 timeframe, when photographs were showing the sudden development of tail-like features well away from the nominal antisolar direction. Their data are consistent with the expulsion of ice particles from the nucleus in an outburst. Cremonese and Fulle (AA 202, L13) observed a DE in comet Bradfield on 1987 December 20. They attributed the sharp bend in the detached tail, if not the disconnection itself, to a change in the solar-wind polar velocity component. Niedner, Brandt, and Yi (AGU) examined the solar wind and IMF properties at Halley at the time of the DE on 1986 January 10, and concluded that reconnection models favoring both sunside and tailward processes were consistent with the data. This was also the conclusion of Niedner and Brosius (Eos, 71, 603), who examined the event in Halley of 1985 December 4-5. Klinglesmith et al (AAS Workshop on Comets, 1990) generated a movie of comet Austin 1989c1 obtained from 14 quasi-wide field (2x2 deg.) CCD frames in the light of H_2O+ (6205 A); the film shows dramatic reorientations of the plasma tail, as well as disconnection effects. Finally, in connection with tail processes and magnetic reconnection in particular, it is worth noting that Verigin et al (GRL 14, 987) and Kirsch et al (AG 7, 107) both reported evidence for a sunside magnetic reconnection origin for energetic particle beams seen both in the Vega and Giotto data during their encounters. These intervals of energetic plasma are correlated with reversals of the IMF. The energization of cometary plasma and associated ionization effects as a result of sector boundary crossing/magnetic reconnection had earlier been discussed by Niedner (ApJ 241, 820).

5. ORIGIN AND EVOLUTION OF COMETS

Recent advances in the understanding of the origin and evolution of comets can be divided into two major areas: orbital studies and physical studies. The areas of the orbital investigations that saw most progress are: perturbations of cometary orbits in the Oort cloud due to the galactic tidal field forces; origin, orbital evolution and dynamical lifetimes of the short-period comets; and effects of chaotic motions. The research areas dealing with the physical aspects of the issue included elemental and isotopic composition of comets; the role of accretion processes, gravitational accumulation of grain aggregates in the protosolar nebula, and the fractal structure of cometary nuclei; and observational evidence for aging of comets and dormant phases in their activity patterns.

Orbital Studies

Delsemme (AA 187, 913) found that most observed Oort-cloud comets were brought to the Sun by the galactic disk tidal field, a notion supported by Matese and Whitman (Ic 82, 389) and Yabushita (Symp. Celest. Mech. Kyoto 21, p. 24). These comets can easily be removed from the observable region (Yabushita, MN 231, 723; AJ 97, 262). Duncan et al (AJ 94, 1330) showed that galactic and stellar perturbations are efficient enough at solar distances greater than 5000 AU to detach comet perihelia from the planetary region. Perturbations of comets in the Oort cloud and their processing there were discussed by Staniucha and Banaszkiewicz (IAU Colloq. 96, 201), Stern (Ic 73, 499; 76, 385; 84, 447), Stern and Shull (Nat 332, 407), and Staniucha (AM 439). New estimates of the mass and angular momentum of comets in the Oort cloud were published by Marochnik et al (Sci 242, 547). A technique for detecting occultations of stars by comets in the Oort cloud was proposed by Axelrod et al (BAAS 21, 1154). Cometary clouds associated with the post-main-sequence stellar evolution were investigated by Stern et al (Nat 345, 305).

Additional discussions on the origin of comets and on the Oort cloud and its structure can be found in various reviews (e.g., Rickman and Froeschle, CM 43, 243; Whipple, AA 187, 852; ApJ 341, 1; Spinrad, ARAA 25, 231; Bailey, ACM, 221; Coangeli et al., ESA 302, 17; Bailey et al., The Origin of Comets, Pergamon, Oxford; Weissman, Nat 344, 825). Comet showers, cratering rates, and related issues were discussed by Bailey et al (MN 227, 863), Clube (ESA 278, 49), Hut et al (Nat 329, 118), Bailey and Stagg (MN 235, 1), Fernandez and Ip (Ic 71, 46), Stothers (Obs 108, 1), Weissman et al (GRL 16, 1241).

In connection with the eruption theory of the origin of comets, proposed by Lagrange and Vsekhsvyatski, Guliev and Bairamov (KFNT 4, 30) classified 32 periodic comets of the Jupiter family into two groups. They found that the rate of secular fading of the comets of one group increased, while that of the other decreased, confirming the conclusion about the youth of comets. Drobyshevski (EMP 44, 7) discussed possible consequences of the explosion of Callisto caused by the accumulated oxygen and hydrogen and proposed this satellite as highest rank target for future space missions. In order to investigate the role of the giant planets in the fate of comets, Babenko and Konopleva (VINITI depos. 5845, B 88) extended their catalogue of the minimal interorbital distances between the orbits of comets and these planets. Investigations of the orbital evolution and lifetimes include P/Halley and other Halley-type comets (Olsson-Steel, AA 187, 909; Hajduk, AA 187, 925; Hajdukova, ESA 278, 645; Sitarski and Ziolkowski, AA 187, 896; Ziolkowski, ESA 278, 747; Carusi et al, AA 187, 899), the sungrazers (Marsden, AJ 98, 2306; ACM, 393), a comet pair 1987XXX-1988III (Marsden, AJ 99, 1971), P/Neujmin 3 and P/Van Biesbroeck (Belyaev and Emelyanenk ACM, 249), P/Ciffreo and P/Maury (Benest et al ACM, 255), and P/Gunn (Todorovic-Juchniewicz, ACM, 459). The dynamical evolution of short-period comets was also studied by Carusi and Valsecchi (PAIC 67, 21).

From their computer simulations, Duncan et al (ApJ 328, L69) argued that the population of short-period comets with their predominantly low inclinations could only be derived from a flat disk lying just outside the orbit of Neptune (Kuiper belt). This conclusion appears to have been strengthened by the subsequent discovery of chaotic motions in this comet disk, with divergence time-scales on the order of only 1 Myr (Torbett, AJ 98, 1477; Torbett & Smoluchowski, Nat 345, 49). On the other hand, Stagg and Bailey (MN 241, 507) emphasized that the capture of short-period comets is a stochastic process, dominated by occasional close encounters with the planets. These recent developments in the understanding of the origin of short-period comets were summarized by Kerr (Sci 239, 1372), Stewart (Nat 343, 17), and Bailey (Nat 345, 21). The Kuiper belt was proposed by Olsson-Steel (MN 234, 389; HA, 313) to be the site of origin for P/Halley.

Physical Aspects

P/Halley's elemental and/or isotopic composition was found to be consistent with its solar system origin by Eberhardt et al (AA 187, 435), Geiss (AA 187, 859; RMA 1, 1), Delsemme (ESA 278, 19), Engel et al (BAAS 20, 827), Grim and Greenberg (AA 181, 155), Solc et al (ESA 278, 359). Encrenaz et al (ESA 278, 369) and Kawara et al (AA 207, 174) found similarities with interstellar dust. Allen et al (AA 187, 502) derived methane and ammonia abundances in Halley unlike those of the outer planets and interstellar gas. Wyckoff et al (ApJ 339, 488) excluded Halley's origin in the Uranus-Neptune region on the basis of the observed $12^c/13^c$ isotopic ratio. The significance of the orthopara ratio of water for the determination of the nuclear ice spin temperature and the site of origin of comets was emphasized by Mumma et al (AA 187, 419; BAAS 20, 826), but Bockelé-Morvan and Crovisier (ACM, 263) questioned their method to retrieve the ratio's value from IR observations.

The accretion processes in interstellar space and the protosolar nebula that are believed to have led to the formation of comets, including the gradual growth of fractal structures, were addressed by Greenberg et al (ASR 9, 3; AP 14, 103), Greenberg and Hage (ApJ, in press), Donn and Meakin (BAAS 20, 840; LPSC, 577), Meakin and Donn (ApJ 329, L39), Lang (ESA 278, 483), Yamamoto and Kozasa (Ic 75, 540), Bar-Nun and Prialnik (ApJ 324, L31), O'Dell (ASR 9, 13), and Celotto et al (ACM, 271). Combining the spacecraft data on the composition of P/Halley's volatiles with experimental results on gas trapping in amorphous ice, Bar-Nun and Kleinfeld (Ic 80, 243) derived information on the gas composition and temperature in the region of formation of this comet.

Among the problems of comet evolution, most attention was paid to observational evidence of physical aging and to mantle formation and orbital evolution. Kresak (AA 187, 906) proposed that periods of a comet's activity are interlaced with dormant phases. Sekanina (AJ 96, 1455) concluded that P/Encke's dormancy could explain the negative results of its searches in ancient and medieval records. Sekanina (AJ 100, in press) also interpreted sudden changes in the nongravitational effects in terms of the birth and extinction of discrete active vents on the nucleus surface and suggested the vents' short life spans. The rate of aging as reflected in long-term brightness variations of comets was studied by Kresak and Kresakova (BAC 40, 269; 41, 1; Ic 86, 82), Whipple (BAAS 20, 1089), Ferrin and Gil (AA 194, 288), and Svoren (ACM, 447). There still appears to be little consensus. Late stages of the physical evolution of comets were reviewed by Rickman (PAIC 67, 37). Various aspects of the evolution of comets into asteroids were discussed by Whipple (PTRS, A323, 339), A'Hearn (AREP 16, 273), Wetherill (Ic 76, 1), Prialnik (ASR 9, 25), Weissman et al (A II, 880), and Kresak and Stohl (ACM, 379). The formation and purging of a dust mantle on the nucleus surface was recognized as one of the most significant developments that affect the evolution of comet nuclei (Johnson et al, AA 187, 889; Sekanina, AA 187, 789; Wallis and Wickramasinghe, ESA 278, 495; Prialnik and Bar-Nun, Ic 74, 272; Smoluchowski, AJ 97, 241; Rickman et al, ACM, 423). The short-period comets whose physical behavior should be followed closely in the future include P/Encke (Sitarski, Acta Astr. 37, 99; ESA 278, 751; Clube and Asher, ACM 275), P/Machholz (Green et al, Sc 247, 1063; Sekanina, AJ 99, 1268), and 2060 Chiron (Hartmann et al, Ic 83, 1; Stern, PASP 101, 126).

The evolutionary significance of the nucleus topography was discussed by Colwell and Jakosky (Ic 72, 128) and by Colwell et al (Ic 85, 205), that of its shape by Jewitt and Meech (ApJ 328, 974). The possibility that cometary nuclei retained their primordial angular momenta was pointed out by Ferrin (Nat 333, 834).

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III. MINOR PLANETS : VINCENZO ZAPPALA

In the following section, the main papers related to asteroid physical studies will be briefly reviewed. Two large meetings have been devoted to this topic in the last three years, the first in Tucson (March 8-11, 1988, "ASTEROID II") and the second in Uppsala (June 12-16, 1989, "ASTEROIDS-COMETS-METEORS III"). The book resulting from the former meeting consists of general review chapters and of tabulated physical and orbital data of asteroids, while the latter conference led to a proceedings book containing contributed papers as well as reviews and reports on specific workshops. Most of the related material will be quoted in the following report, but the readers are invited to look directly into these sources for a more complete overview.

1. LIGHTCURVES, ROTATION RATES, SHAPES, MASSES

Continuing the trend of the past years, numerous lightcurves of asteroids have been derived by astronomers of different countries and geographic areas, including Europe, the United States, South America, and the Soviet Union. In addition to papers devoted to specific asteroids (Lagerkvist et al, AASS 70, 21; Melillo, MPB 14, 21 and MPB 14, 42; Hollis, JBAA 98, 14, JBAA 98, 255 and JBAA 98, 351; Binzel et al, Ic 71, 148; Schober, AA 183, 151; Gallardo and Tancredi, RMAA 15, 103; Hutton, MPB 15, 21, MPB 15, 39 and MPB 16, 16; Hutton and Blain, MPB 15, 3; Zeigler and Wampole, MPB 15, 15; Schober et al, AA 197, 327; Velichko et al, AV 22, 136; Lupishko et al, AV 22, 167; Harris et al, Ic 77, 171; Hahn et al, Ic 78, 363; Debehogne et al, ACM III, 45; Hoffmann and Geyer, ACM III, 111; Erikson, ACM III, 55; Miles, MPB 16, 16; Schober and Stadler, AA 230, 233; Di Martino et al, AA 223, 352; Aksenov et al, PAZh 13, 616; Tancredi and Gallardo, BAAA 33, 361), two studies presented lightcurves for large sets of asteroids (Binzel, Ic 72, 135 observed 130 asteroids mainly belonging to Eos and Koronis families; and Harris and Young, Ic 81, 314 reported on observations of 70 asteroids). Harris and Lupishko (A II, 39) presented a thorough review of the methods to obtain and reduce photometric lightcurves, as well as to extract from them the most important parameters.

CCD photometry has been used for obtaining lightcurves of faint asteroids (French, Ic 72, 325; French et al, BAAS 20, 857; Blanco et al, MSAI 60, 195; Mottola et al, ACM III, 151), clearly showing how fruitful this technique can be for enlarging the present data set to very small and/or distant asteroids. French and Binzel (A II, 54) discussed the relative merits and drawbacks of this technique when applied to asteroid photometry. Infrared lightcurves were obtained for asteroids 532 Herculina and 45 Eugenia by Lebofsky et al (Ic 75, 518), showing that their light variations are primarily due to shape rather than to albedo variegations. Vdovichenko et al (AV 22, 147) presented lightcurves of 4 Vesta in the pyroxene band.

Of particular importance are observations devoted to outer belt asteroids. The results obtained by French (Ic 72, 325 and BAAS 19, 850), Hartmann et al (Ic 73, 487), French et al (BAAS 20, 857), Hartmann (BAAS 19, 850), Mottola et al (ACM III, 151), Zappala et al (Ic 82, 354), Rebhan et al(BAAS 21, 966) generally indicate that the rotations and shapes of outer belt asteroids have peculiar features when compared with the same properties of main belt objects. In particular, Trojan asteroids seem to be more elongated than main belt objects of comparable size. Statistical tests and speculative explanations on this topic have been presented by French (Ic 72, 325), Hartmann et al (Ic 73, 487) and Zappala et al (Ic 82, 354). A more general discussion can be found in French et al (A II, 468).

A sudden brightening observed on 2060 Chiron was discussed by Stern (PASP 101, 635). It seems plausible that this object could have formed in and come from the inner Oort cloud. R-band CCD photometry was carried out by Bus et al (Ic 77, 223), allowing the determination of the rotation period and the small (0.088 mag) lightcurve amplitude. Apart from this, no evidence of periodic or nonperiodic brightness changes was found, and the authors suggested the possibility that Chiron's intrinsic brightness has remained stable over the past decade, with an excursion of about 0.56 mag on a time scale of a few years. Hartmann et al (Ic 83, 1) performed VRIJHK colorimetry, confirming that Chiron was brighter by about 0.6 mag in February-March 1988 and by about 1.0 mag in September-October 1988 relative to the absolute magnitude determined in 1980 and 1983. The data are consistent with the hypothesis that Chiron undergoes cometary outbursts, and the authors suggest that Chiron should be considered as the largest observed comet nucleus (180 km in size). CCD observations of Chiron in 1984-85 have been also reported by Marcialis (BAAS 21, 965), who did not find any evidence of activity. The case of Chiron is discussed in details by French et al (A II, 468).

New photoelectric observations and careful analysis of existing data allowed the determination of the magnitude-phase relationship for several asteroids. Lagerkvist et al (AASS 73, 395 and AASS 78, 519) obtained G and H values for more than 80 objects. Skoglov et al (ACM III, 183) deduced phase curves using the lightcurves reported in the Asteroid Photometric Catalogue. Other magnitude-phase relationships were obtained by Harris and Young (BAAS 20, 865) and Harris et al (Ic 81, 365). Domingue and Hapke (Ic 78, 330) discussed the present theories on this issue and their application to actual asteroids, while Capaccioni et al (Ic 83, 325) investigated the phase curves of a sample of meteorites and lunar rocks, comparing the results with those of the asteroids. Zappala et al (AA 231, 548) studied the amplitude-phase relationships for a sample of asteroids and compared them with the results of numerical and laboratory models. They found a possible correlation between the slope of the amplitude-phase relationship and the taxonomic type. This finding, however, is not fully consistent with the results of the theoretical approach developed by Karttunen and Bowell (AA 208, 320).

The problem of determining the polar direction, sense of rotation and shape of asteroids has been extensively dealt with in recent years. Several new determinations of poles and shapes were obtained (Lupishko et al, KFNT 5, 36; Taylor et al, Ic 73, 314; Velichko and Lupishko, KFNT 5, 90; Michalowski, AcA 38, 455; Binzel, ACM III, 15; Gallardo and Tancredi, ACM III, 87; Lupishko and Velichko, ACM III, 139; Michalowski and Kwiatkowski, ACM III, 147; Drummond and Wisniewski, Ic 83, 349; Birch and Taylor, AASS 81, 409). In particular, papers concerning large asteroid samples were published by Drummond et al (Ic 76, 19) and Magnusson (Ic 85, 229). New methods for pole determination based on lightcurves analysis were presented by Uchida and Goguen (BAAS 19, 842) and Lumme et al (AA 229, 228).

Cellino et al (AA 219, 320) showed that the shape and pole of Vesta derived by photometric data is in a good agreement with the results obtained with speckle interferometry (Drummond et al, Ic 73, 1). More generally, a check of the different methods commonly used for pole and shape determination was carried out by applying all of them to a set of fictitious lightcurve data coming from a synthetic model. The results were in fairly good agreement, providing further confidence in the existing procedures (Karttunen et al, ACM III, 119).

Several papers were also devoted to the problem of the inversion of asteroid lightcurves, either taking into account or neglecting the possible contribution of albedo variegation (Ostro et al, Ic 75, 30; Karttunen, AA 208, 314; Karttunen and Bowell, AA 208, 320; Hainaut et al, ACM III, 99; Kaasalainen et al, ACM III, 115).

Cellino et al (Ic 78, 298) showed that irregular but "realistic" shapes can produce very irregular lightcurves, having intriguing analogies with some puzzling asteroid lightcurves. Barucci et al (Ic 78, 311) made a statistical study of the 2,254 lightcurves contained in the Asteroid Photometric Catalogue by means of Fourier analysis. They derived a description of possible shape and albedo variations for some specific asteroids, and suggested that about 30-40% of the asteroids show indications of albedo patches. An extensive review of the methods for pole and shape determination is given in Magnusson et al (A II, 66), where the potential of new techniques, like radar and speckle interferometry, is emphasized.

The problem of the mass and mean density determination of asteroids was discussed by Hoffmann (A II, 228), who described the most promising methods in this field. An improved determination of the mass of Ceres from the perturbations on the orbit of Pallas was reported by Landgraf (AA 191, 161), while Hoffmann (Ic 78, 280) described the method based on the close encounters between asteroids. Standish and Hellings (Ic 80, 326) determined the masses of Ceres, Pallas, and Vesta from their perturbation upon the orbit of Mars.

2. STRUCTURE, MORPHOLOGY, MINERALOGY, PETROLOGY, TAXONOMY

Special efforts were made by applying well known and/or new techniques in order to improve the knowledge of asteroid mineralogy and composition, determine the sources of near-Earth asteroids and meteorites, and in particular to solve the "paradox" of ordinary chondrites, the most common meteorites, that seem to be spectrally distinct from almost all asteroids. On the latter issue, different possibilities were suggested. First, the present mineralogical interpretations could be wrong, due to some poorly understood process suffered by meteorites upon entering the Earth's atmosphere or some alteration mechanism connected with the formation of asteroid regoliths. Alternatively, it is possible that the parent bodies of ordinary chondrites in the main asteroid belt may have escaped spectroscopic detection due to their small sizes. This possibility was discussed in detail by Bell et al(A II, 921). Other analyses of the same problem were presented by Gaffey et al (A II, 98), Lipschutz et al (A II, 740), and Binzel (A II, 3).

Spectral surveys were carried out over a wide range of wavelengths, including (passive) microwave observations. Vilas and McFadden (BAAS 19, 825) obtained spectra of Ceres in the range 0.53-0.60 microns and presented new CCD reflectance spectra of outer belt asteroids. McFadden and Vilas (BAAS 19, 841), continuing the search for spectral analogues of ordinary chondrites, studied the spectral reflectance of asteroids near the 3:1 Kirkwood gap; a similar search, also including near-Earth asteroids, was performed by Luu and Jewitt (ACM III, 143) in the region of 0.48-0.72 microns.

A high-resolution CCD spectral survey was reported by Sawyer (BAAS 20, 856). Golubeva and Shestopalov (AV 22, 173) found by spectral analysis a mineral inhomogeneity on Vesta's surface. Golubeva (AV 22, 49) constructed diagrams of spectral parameters for asteroids with known albedos and spectral data in the region 0.40-0.75 microns, and compared them with the corresponding diagrams of light stone meteorites.

Radiometry data of the asteroid 1984KB were obtained by Bell et al (Ic 73, 482), suggesting that this object has a significant regolith in spite of its small size. Mid-IR reflectance spectra of C-type asteroids were obtained by Jones et al(BAAS 19, 841), while Gradie and Tedesco (BAAS 20, 866) reported albedos and diameters for 350 asteroids from the IRTF 10 and 20 micron radiometry survey. Twenty-two Apollo-Amor-Aten asteroids were observed by infrared photometry at 10 microns by Veeder et al (AJ 97, 1211), to derive the corresponding radiometric albedos and diameters. They confirmed that low albedos remain rare among near-Earth asteroids. Broadband and narrowband spectrophotometry (1.2 to 3.5 microns) was presented by Lebofsky et al (Ic 83, 16) for 16 low albedo asteroids. These authors found that most of these objects do not show the spectral signature of hydrated silicates, at odds with the previous assumption that outer belt and Trojan asteroids are more primitive than C-type objects and thus should show a larger volatile content.

Cruikshank and Brown (Sci 238, 183) presented infrared absorption spectra of the low-albedo asteroid 130 Elektra, indicating the presence of hydrocarbons and showing spectral bands similar to those of the organic extract from the primitive carbonaceous Murchison meteorite.

Redman et al (ACM III, 163) have obtained submillimetre spectra of the asteroids Juno, Vesta, Iris and Hesperia, possibly showing evidence of the presence of 100-micron sized particles in their surface regolith.

The microwave spectrum of Ceres was obtained at wavelengths between 3.3 mm and 20 cm by Webster et al (AJ 95, 1263), while Johnston et al (AJ 98, 335) investigated Pallas, Vesta, and Hygiea at 2 and 6 cm. It follows that these asteroids are probably covered by a layer of material with the physical properties of finely divided dust; no evidence for water ice was found.

Webster and Johnston (PASP 101, 122) pointed out that observations of the microwave continuum spectrum of asteroids show that the cm-wavelength emissivity is nearly 25% lower than both the mm-wavelength and the infrared emissivity, and is constant between 2 and 20 cm. Major modifications to the conventional physical parameters used in treating single-wavelength observations are thus required when the observing wavelength is longer than about 1 cm. General reviews about reflectance spectroscopy, radiometry and passive microwave observations, are given in the papers by Gaffey et al (A II, 98), Lebofsky and Spencer (A II, 128), and Webster and Johnston (A II, 213), respectively.

The major impacts of IRAS observations on asteroid studies were reported by Matson et al (A II, 269), Veeder et al (A II, 282), and Tedesco et al (A II, 290). Lebofsky (Ic 78, 355) pointed out that a systematic variation (with wavelength) in the IRAS model diameters for even the brightest asteroids can lead to overestimates of the sizes by as much as 5-10%. This wavelength dependence of the IRAS asteroid data is a complex and still unsolved issue.

Radar observations have been focused on near-Earth asteroids (Yeomans et al, BAAS 19, 840). In the case of the object 1986DA, they clearly indicate a metal-rich composition (Ostro et al, BAAS 19, 840). Other more recent observations were performed and reported by Ostro et al (BAAS 20, 863 and BAAS 21, 963), while Ostro et al (Ic 78, 382), using the Goldstone 3.5-cm wavelength radar, obtained echoes from the asteroid 1986JK only three weeks after discovery. In addition, Ostro et al (Ic 84, 334) used the echo spectra obtained in 1975 for a new precise determination of the shape of 433 Eros. A detailed review of the radar technique is given by Ostro (A II, 192).

New speckle interferometry results were obtained for 4 Vesta (Drummond et al, Ic 73, 1; Vakulik et al, PAZh 15, 368). A discussion of the method is given by Drummond and Hege (A II, 171).

Polarimetric observations have been also devoted mainly to Vesta (Lupishko et al, AV 22, 142; Shkuratov, AV 22, 152; Broglia and Manara, AA 214, 389). In addition, Kolokova and Yanovitskij (KNFT 4, 82) indicated a new possibility to derive asteroid diameters from polarimetric data. Dollfus (ACM III, 49) addressed the importance of polarimetry for the study of asteroid regoliths, while Dollfus et al (A II, 594) presented a detailed review on photopolarimetry of asteroids.

New important occultation campaigns have been successful. Millis et al (Ic 72, 507) reported on the event involving the star BD +8 471 and Ceres, inferring for the largest asteroid a mean density of about 2.7 g/cm3 and a shape which fits quite well a hydrostatic equilibrium figure. Qian et al (AAS 29, 125) observed the occultation of the star SAO 41263 by 324 Bamberga. Drummond and Cocke (Ic 78, 323) used the two available stellar occultations by Pallas for deducing its triaxial shape and pole. Finally, Millis et al. (Ic 81, 375) determined the diameter, shape, albedo and rotation of asteroid 47 Aglaja by combining occultation data obtained in 1984 with photometric observations. A discussion of the importance of stellar occultations for precise measurements of asteroid sizes and shapes and calibration of other methods is given by Millis and Dunham (A II,148).

The large set of data supplied by IRAS on asteroid albedos led to new taxonomic classifications. Barucci et al (Ic 72, 304) used a revised version of the G-mode multivariate statistics to classify the 438 asteroids for which eight-color photometric data and IRAS albedos are available. In total, they distinguished 18 groups of objects. Tedesco et al (AJ 97, 580) used three parameters only (U-V, v-x, and geometric albedo) to create a classification algorithm that places 96% of their sample of 357 asteroids into 11 taxonomic classes. The distribution of taxonomic types with respect to heliocentric distance was analyzed by Chapman (Met 22, 353), while Davis (ACM III, 39) tried to interpret the differences in size distribution of the taxonomic types in terms of collisional evolution. Hahn and Lagerkvist (Ic 74, 454) performed new JHK photometry for 77 asteroids, and then plotted a sample of 151 objects in the J-H vs H-K plane, investigating the position of all the taxonomic types. The present status of asteroid taxonomy and the comparisons between the existing classifications was reviewed by Tholen and Barucci (A II, 298), while the distribution of taxonomic classes and the compositional structure of the asteroid belt were thoroughly discussed by Gradie et al (A II, 316).

The composition and mineralogy of Ceres was studied by Celebonovic (EMP 42, 297) and Fanale and Salvail (Ic 82, 97), who analyzed in particular the water regime of the largest asteroid. Gaffey (ACM III, 77) presented a study on the implications of asteroid surface mineralogy for the evolution of the inner belt.

3. ORIGIN AND EVOLUTION

The formation of asteroids from planetesimals and the way planetary growth was stopped in the belt have been recently reassessed, in the frame of new results on the dynamics of planetesimal interaction and accumulation. The possible onset and the successive quenching of runaway growth, with time scales smaller than 1 Myr, possibly provides a mechanism for "tuning" the timing of the asteroid formation and early evolution phases with that of Jupiter (see the review by Wetherill, A II, 661). Sweeping secular resonances (Lemaitre and Dubru, Rep. Univ. Namur 90/03) and short-lived massive bodies coming from the Jovian zone (Ip, Beitrag, Geophysik 96, 44) have been quantitatively assessed as promising candidates for stirring up asteroid eccentricities and inclinations, and/or for ejecting a large fraction of the initial asteroid mass.

Data from meteorites have provided many constraints on the properties (number, size, composition, thermal history) of their parent bodies, especially after the abundant Antarctic meteorite sample has become available (Lipschutz et al, A II, 740). As quoted earlier, however, it has proven difficult to reconcile the spectral properties of the most abundant meteorites (ordinary chondrites) with those of any asteroid type apart from the rare near-Earth Q type. This is at odds with the results of dynamical studies that point to the 3:1 mean motion and the nu6 secular resonances as the most likely routes through which asteroidal fragments can be delivered to Earth-crossing orbits (Greenberg and Nolan, A II, 778). Large uncertainties, however, affect quantitative models aimed at estimating the efficiency of various delivery mechanisms. In this respect, the study of the known Earth-crossing asteroids is of crucial importance.

Hahn (PhD Thesis, Uppsala Univ.) has performed a detailed study on the physical and dynamical features of planet-crossing asteroids. A new classification of their long-term dynamical evolution was proposed by Milani et al (Ic 78, 212). Wetherill

(Ic 76, 1) investigated the origin of the Apollo-Amor objects, while Olsson-Steel (ACM III, 159) discussed the association of meteoroid streams with many of these asteroids.

Collisions -- and especially catastrophic events -- are widely believed to represent the main process currently causing the asteroid population to evolve. Quantitative models of this evolution have been developed, and they appear to imply that the total asteroid mass has decreased by a factor of 2 to 5 since the onset of the high-velocity impact regime and that most asteroid spins have undergone drastic collisional changes (Davis et al, A II, 805). However, the reliability of these models is limited by the scarcity of laboratory results on the outcomes of catastrophic collisions (especially on fragment ejection speeds and rotations) and by the complex physical problems involved in scaling up to asteroid sizes experimental results. These issues were reviewed by Fujiwara et al (A II, 240).

Paolicchi et al (Ic 77, 187) presented a simple theoretical model to derive the observable properties of fragments from a suitable velocity field of the target material, assumed to arise from the explosion due to the impact and from the original rotation of the target. Some observed properties of the main asteroid families are well reproduced by the model, and observable correlations among ejection velocity, size, rotation, and shape can be predicted. Di Martino et al (Ic 83, 126) studied the process of catastrophic fragmentation and the associated production of dust, analyzing results coming from laboratory hypervelocity impacts. They concluded that at least two separate disruption mechanisms (cratering and bulk fragmentation) operate over two different time scales. Housen and Holsapple (Ic 84, 226) derived a general scaling theory that guides the extrapolation of small-scale experimental results.

Asteroid families are probably the best observable results of catastrophic fragmentations in the solar system; as a consequence, their study is a powerful tool to look into asteroid interiors and get first-hand information on break-up mechanisms. However, difficult problems arise in their identification within the background of non-family asteroids, preventing reliable quantitative analyses.

Williams and Hierath (Ic 72, 276) used P-L asteroids for enlarging the sample of previously identified Williams families. Williams (BAAS 19, 824) pointed out the presence of very peculiar and poorly understood groupings. New high-order and high-degree theories of planetary perturbations (Knezevic et al, AA 192, 360; Valsecchi et al, A II, 368) led to the derivation of precise proper elements for a larger (about 4,100) number of asteroids. Zappala′ et al (ACM III, 211) applied to this sample a new "hierarchical clustering method" and detected some 15 families having a high degree of robustness and reliability. Other studies on this topic were made by Binzel (Ic 73, 303), who analyzed the collisional evolution of two well-known and reliable families (Eos and Koronis) in terms of their observed spin rate distribution; by Farinella et al (AA 217, 298), who assessed the available methods for estimating the age of families; by Hoffmann (ACM III, 109), who studied the structure of the Eos, Koronis, and Themis families by treating them as analogues of stellar clusters; by Takagi and Mizutani (ACM III, 191), who investigated the families′ formation by catastrophic impact events; and by Bell (Ic 78, 425), who investigated the mineralogical composition of the parent bodies of families from the existing taxonomic classifications. He found that only the few largest and well-defined families probably consist of fragments from collisionally disrupted parents, while most other proposed groupings cannot have such an origin.

This problem and the general issue of asteroid families have been reviewed by Chapman et al (A II, 386), who also give speculative explanations for the relatively small number of families consistent with simple cosmochemical models, despite the expected extensive collisional evolution of asteroids.

Correlations of spin rates with taxonomic types, shapes, and family membership (but not with orbital parameters) have been found (Binzel et al., A II, 416). Shestopalov (KFNT 4, 67) showed that the V-shape distribution of asteroid spins as correlated to the regolith thickness. Harris (Ic 83, 183) studied the collisional evolution of the spin of a nonspherical body, finding that deviations from spherical geometry do not significantly affect the results of his previous models.

The existence of binary asteroids, their possible formation mechanisms, and their dynamics were discussed by Weidenschilling et al (A II, 643). The problem of assessing whether binary asteroids are dynamically stable with respect to external perturbations has been investigated by Chavineau and Mignard (Ic 83, 360).

The dust bands found by the IRAS survey was analyzed by Sykes (BAAS 19, 825 and BAAS 20, 862), who suggested the likely existence of a larger number of asteroid dust bands and pointed out the presence of dust in the Koronis family. This topic was also reviewed by Sykes et al (A II, 336).

Many papers dealing with purely dynamic studies of asteroids have appeared in the literature; they are listed in the reports of other IAU Commissions (nos.7, 20); recent reviews are those of Froeschle and Greenberg (A II, 827), Scholl et al.(A II, 845), Nobili (A II, 862), and Weissman et al (A II, 880).

ADDITIONAL REFERENCES

AA: Astronomy and Astrophysics; AAS: Acta Astronomica Sinica; AASS: Astronomy and Astrophysics Suppl. Series; AcA: Acta Astronomica; AG: Annales Geophysicae; AGU: Proc. AGU Chapman Conference on Cometary Plasmas held in Guildford, UK, 1989 July 17-21, in press; AN: Astron. Nachrichten; AJ: Astron. Journal; AP: Annales de Physique, Paris; ASR: Astrophys. Space Res. Vol. 9: No 3, in press; ATAO: Ann. Tokyo Astron. Obs. 22, 2nd series, No. 1; AV: Astronomicheskij Vestnik; BAAA: Bul. Assoc. Argent. Astron.; BAAS: Bul. Amer. Astron. Soc.; BDM: Baryonic Dark Matter (eds D. Lynden-Bell, G. Gilmore, Kluwer Acad. Publ., 1990); CPHE: Comets in the Post-Halley Era (eds R.L. Newburn, M. Neugebauer, J. Rahe, Kluwer Acad. Publ., in press, 1990); ECDA: Experiments on Cosmic Dust Analogues (eds. E. Bussoletti, C. Fusco, G. Largo, Kluwer Acad. Publ., 1988); EID: Proc. Internat. School of Physics (Enrico Fermi), Course CI, Evolution of Interstellar Dust and Related Topics; EMP: Earth, Moon, and Planets; ESA SP-278: Symposium on the Diversity and Similarity of Comets (eds E.J. Rolfe and B. Battrick, 1987); ESA SP-290: 22nd Eslab Symposium, Infrared Spectroscopy in Astronomy (ed B.H. Kaldeich, 1989); ESA SP-302: International Workshop on Physics and Mechanics of Cometary Materials (eds J.Hunt and T.D. Guyenne, 1989); HA: Highlights of Astronomy; HWWI: Comet Halley 1989, World-Wide Investigations, Results and Interpretations (Ellis Horwood Ltd, in press, 1990); IAM: Institute for Applied Mechanics, Moscow: Preprint Series; IAUC: IAU Circular; Ic: Icarus; ISD: IAU Symposium No. 135: Interstellar Dust; JBAA: Journ. Brit. Astron. Soc.; KFNT: Kinematika i Fisika Nebesnykh Te.; KI: Kosmicheskie Issledovaniya Akademiya Nauka SSR (Engl. Translation in Cosmic Research); Met: Meteoritics; MPB: Minor Planet Bulletin; MSAI: Memorie della Societa' Astronomica Italiana; NASA CP 3004: Infrared Observations of Comet Halley and Wilson and Properties of the Grains (ed M.S.Hanner, 1988); OPSA: Origin and Evolution of Planetary and Satellite Atmospheres (eds S.K. Atreya et al., Univ. Arizona Press, Tucson, 1990); PAIC: Publ. Astron. Inst. Czechoslov. Acad. Sc. 67, No 2, Interplanetary Matter (eds Z. Ceplecha and P. Pacina, 1987); PASP: Publ. Astron. Soc. Pacific; PAZh: Pis'ma Astron. Zh.; PCC: Physics and Chemistry of Comets (ed W.F. Huebner, Springer Verlag, in press, 1990); PhR: Physical Review; RMAA: Rev. Mex. Astron. Astrofis.; Sci: Science; AII: Asteroids II (eds R.P. Binzel, T. Gehrels, M.S. Matthews, Univ. Arizona Press, Tucson, 1989); ACM III: Asteroids, Comets, Meteors III (eds. C.I. Lagerkvist, H. Rickman, B.A. Lindblad, M. Lindgren, Uppsala Univ. Reprocentralen, 1990).

IV. METEORITES : H.J. MCSWEEN, J.T. WASSON

1. INTERPLANETARY DUST - J. Bradley: An SEM study of 200 chondritic interplanetary dust particles (IDPs) showed that the hydrated (layer silicate) subset are systematically depleted in Ca and Mg (Schramm et al, Met 24, 99-112). Evidence for primordial vapor phase condensates in IDPs was obtained from a study of Mn abundances (Klöck et al, Nat 339, 126). Trace-element and isotopic abundances can distinguish non-chondritic extraterrestrial particles from terrestrial contaminants (Stadermann et al, LPS 21, 1190; Flynn and Sutton, LPSC 20, 335; Lindstrom and Zolensky, LPS 21, 700). Electron transparent thin sections facilitated comparison of IDPs, meteorites, and comet Halley grains (Bradley, GCA 52, 889, Jessberger et al, Nat 332, 691). Calculated orbital trajectories, solar-flare tracks, and laboratory heating experiments yielded relative contributions of comets and asteroids to IDP collections (Sandford, Ic 68, 337; Flynn Ic 77, 287; Sandford and Bradley, Ic 82, 146). Mineralogical classes of chondritic IDPs have been characterized (Rietmeijer, LPSC 19, 513; Thomas et al, LPS 21, 1250). Micro- meteorites were recovered from polar ices (Maurette et al, Sci 233, 869; LPS 20, 636) and their extraterrestrial origins confirmed by Ne isotopic measurements (Olinger et al, EPSL, in press). He and Ne concentrations and isotopic abundances suggest exposure of cosmic deep sea spheres to solar flares (Nier et al, GCA 54, 173).

2. PETROLOGY AND COMPOSITION OF CHONDRITES - D.W. Sears: Compilations of recent INAA data for the bulk compositions of the chondrite classes were published by Kallemeyn et al. (GCA 53, 2747; Kallemeyn (Met 23, 278) suggested that the metamorphosed C chondrites constitute a new chondrite class. Several new anomalous chondrites have been reported: ALHA85085 (Scott, EPSL, 91, 1; Grossman et al., EPSL, 91, 33; Weisberg et al., EPSL 91, 19); Carlisle Lake, ALHA85151 and Y-75302 (Rubin and Kallemeyn, GCA 53, 3035; Weisberg et al., LPS 20, 1191); Lea County 002 (Zolensky et al., Met 24, 227); Deakin 001 (Bevan and Binns, Met 24, 135); LEW85332 (Rubin and Kallemeyn, LPS 21 1045). New studies of brecciation (Scott et al., LPSC 18 513; Fayetteville consortium, GCA 53, 1435-1467), aqueous alteration (Hutchison et al., GCA 51, 1875; Guimon et al., GCA 52, 119), shock (Sneyd et al., Met 23, 139) and metamorphism (Sears and Hasan, SG 9, 43; Scott and Jones, Met 24, 324; McSween and Patchen, Met 24, 219; Brearley, GCA, 54, 831) have been reported. A metamorphosed CI chondrite (Y-82162) was discovered (Tomeoka et al., Proc. NIPR Symp. Ant. Met. 2, 36).

3. DIFFERENTIATED STONY METEORITES - H. Takeda: Ureilites have many characteristics of igneous rocks, but oxygen isotope anomalies similar to those in CV3 chondrites (Clayton and Mayeda, GCA 52, 1313) link them with "nebular" meteorites. Various models for impact formation of ureilites were proposed; Rubin (Met 24, 73) suggested impact-melting of carbonaceous chondritic material, and Warren and Kallemeyn (Met 24, 233) that ureilites originated when paracumulates and other materials were intermixed by an impact. Ureilite compaction experiments (Walker and Agee, Met 23, 81) showed that oriented fabrics may also be produced by crystal growth in a temperature gradient. A planetesimal-scale collision model (Takeda, EPSL 93, 181) can account for the relationship between oxygen isotope anomaly and Mg/(Mg+Fe) ratios. Phase equilibrium constraints (Longhi and Pan, LPSC 18, 459) showed that crystallization at 2 kbar can account for the HED association. Characterization of a eucrite with high metal content (Camel Donga, Palme et al., Met 23, 49), the high-Mgo, yet REE-rich eucrite Pomozdino (Warren et al., LPSC 20, 281) and the REE-poor Y-791438 (Saiki et al., LPS 21, 1061) revealed the diversity of processes on the HED parent body. Studies of the second and third ADOR allowed better assessment of their connection with HED (McKay et al., Met 24, 302).

4. IRON METEORITES - K.L. Rasmussen: New iron meteorites were classified (Wasson et al., GCA 53, 735). Revised diffusion rates and phase diagram measurements were published for the Fe-Ni-P system (Saikumar et al., GCA 52, 715; Reuter et al., GCA 52, 617; MT 20A, 711; and MT 20A, 719). New cooling rates were published for groups IIIAB, IVB, IAB and IIICD (Rasmussen Ic 80, 315; Physica Scripta 39, 410). Accelerator mass spectroscopy was applied to iron meteorites (Sutton et al., GCA 51, 2653; Aylmer et al., EPSL 88, 107; Rasmussen et al., Nucl. Instr. Phys. Res. 36, 43 and 43, 256). Chen et al. (GCA 54, 1729) measured Ag isotopes in irons, and

found clues for extinct Pd. Höfler et al. (EPSL 90, 1) made neutron diffraction on macroscopic structures in iron meteorites. Large scale variations of the position of the 3-ton Chinese iron Armanty were investigated (Wasson et al., Met 23, 365).

5. LUNAR METEORITES - O. Eugster: Augmenting the earlier discovery that seven meteorites collected in Antarctica originated from the lunar highlands, four Antarctic meteorites were recognized to be rocks ejected from the lunar mare regions (Delaney, Nat 342, 889; Warren and Kallemeyn, GCA 53, 3323; Takeda et al., SAM 15, 100; Yanai and Kojima, SAM 15, 129). Lunar meteorites from the highlands are anorthosites, but mare meteorites consist largely of very-low-titanium (VLT) materials (Lindstrom, SAM 15, 114; Kurat et al., SAM 15, 193). Cosmic-ray exposure histories and terrestrial ages were derived from noble gases by Eugster (Sci 245, 1197) and from radionuclides by Nishiizumi et al. (Met 23, 294) and Vogt and Herzog (LPS 21, 1274); most lunar meteorites were ejected from the moon <1 Ma ago and fell on Earth within the part <300 ka ago. The meteorites from the highlands originate from at least two different source craters. If the four mare meteorites represent separate source regions, the VLT-basalt is relatively common despite its rarity among rocks returned by the Apollo missions.

6. CRATERING - F. Hörz: The encounter of Voyager 2 with Neptune completed our first order inventory of impact craters in the solar system with spectacular images of heavily cratered terranes on Triton (Smith et al., Sci 246, 1422). The book by Melosh (Impact Cratering) will greatly aid the interpretation of this record. New impact structures were discovered and dated leading to refined terrestrial crater production rate (Bottomley et al., LPSC 20, 421). The challenge to understand large scale, terrestrial impacts and their potentially catastrophic consequences continues to galvanize a highly diverse community. To this end, two international conferences brought a variety of experimental and theoretical insights to large-scale, catastrophic impacts (Nicolaysen and Reimold, Tec 171; Sharpton and Ward, GSASP 247, in press). Two significant "planetary" events were investigated in additional detail: the formation of the Moon from collisional debris resulting from the collision of a Martian sized object with the proto-Earth (Benz et al., Ic 81, 113), and the ejection of relatively young Martian basalts into Earth-crossing orbits to yield the unusual SNC meteorites (O'Keefe and Ahrens, Sci 234, 346; Ott, GCA 52, 1937).

7. IMPACT RECORD IN SEDIMENTS - F.T. Kyte: In October 1988, Snowbird, Utah, USA was the site of a meeting on "Global catastrophes in Earth History: an interdisciplinary conference on impacts, volcanism and mass mortality" (GSASP 247). KT boundary discoveries include potential findings of stishovite (McHone et al., Sci 243, 1182) and tsunami (Bourgeois et al., Sci 241, 567) and proximal-impact deposits (Hildebrand and Boynton, Sci 248, 843; Bohor and Seitz, Nat 344, 593) in the Gulf of Mexico-Caribbean region. Further developments in KT boundary models include global wildfires (Wolbach et al., Nat 334, 665) and impact-produced CO_2 (O'Keefe and Ahrens, Nat 338, 247) and acid raid (Prinn and Fegley, EPSL 83, 1). Historical reviews of a decade of KT debate are given by Glen (AS 78, 354) and 25 years of impact research by French (Eos 71, 411). New information on Ir-rich impact deposits outside the KT boundary include those from the late Pliocene (Kyte et al., Sci 241, 63), the Proterozoic (Gostin et al., Nat 340, 542) and the Archean (Lowe et al., Sci 245, 959).

8. REFRACTORY INCLUSIONS - G.J. MacPherson: Research on refractory inclusions involved experimental investigations of processes and multiple techniques to document complex histories. Hashimoto et al. (Met 24, 275) volatilized forsterite and observed large mass fractionation isotopic effects in Mg, Si and O in the residues provided melting occurs. A new FUN inclusion from CV3 Vigarano, although mineralogically very different, is isotopically the twin of the well-studied C1 inclusion (Loss et al., LPS 21, 718). MacPherson et al. (GCA 53, 2413) showed that a type-B inclusion formed by fractional crystallization plus assimilation of foreign grains. Beckett et al. (GCA 54, 1755) and Kuehner et al. (GCA 53, 3115) studied the trace-element partition into melilite. Blum et al. (GCA 53, 483 and 543) showed that the mineral assemblages in Fremdlinge result from secondary processes. Podosek et al. (LPS 20, 856) used studies of Rb-Sr and Mg-Al isotopes in CAI to argue that a heterogeneous distribution of ^{26}Al in the early solar system is not required. ALH85084 contains a new class of tiny (<100 μm) inclusions consisting of hibonite enclosed in glass (Grossman et al., EPSL 91, 33).

9. CHONDRULES AND MATRIX - R.H. Jones: The application of transmission electron microscope techniques led to advances in matrix studies. Fine-grained matrix in OCs could be the product of high-temperature annealing of amorphous presolar dust or nebular condensates (Brearley et al., GCA 53, 2081); alternatively it may have been formed by fragmentation of chondrules (Alexander et al., EPSL 95, 187). Hutchison et al. reported evidence for hydrothermal alteration in UOC matrix (GCA 51, 1875). The early stages of aqueous alteration were studied by Keller and Buseck (GCA 54, 1155). Mass balance constraints on the matrix mineralogy of CM and CI chondrites provided a model for aqueous alteration processes (McSween, GCA 51, 2469). Matrix may be the ^{16}O-poor component of Allende chondrules and their rims (Rubin et al., EPSL 96, 247). REE fractionations and variations in volatile contents were established during formation of the precursors of Allende chondrules (Misawa and Nakamura, GCA 52, 1699). In Semarkona some chondrules experienced fractional evaporation when molten (Grossman and Wasson, GCA 51, 3003). Fa-rich PO chondrules in Semarkona contain relict Fo grains with compositions similar to Fo-rich PO chondrule olivines (Jones, GCA 54, 1785). Dynamic crystallization experiments show that chondrule textures are primarily controlled by heterogeneous nucleation (Lofgren, GCA 53, 461), and that a narrow range of peak temperatures was experienced by all chondrules (Radomsky and Hewins, Met 23, 297). Hewins (MNIPR 30, 93) proposes that chondrule formation took place in localized, hot, particle-rich zones in the nebula. Levy and Araki (Ic 81, 74) examine the possibility that chondrule formation took place in magnetic reconnection flares.

10. NEBULAR CONDITIONS - J.A. Nuth: The isolation of demonstrably presolar diamonds (Lewis et al. NAT, 326, 160), diamond-like hydrocarbon (Ming and Anders GCA 52 1245), SiC (Tang et al. NAT 339, 351) and graphite (Amari et al. NAT 345, 238) in all unmetamorphosed chondrite types (Huss and Lewis LPS 21 542) argues that the global environment in the region of chondrite formation did not exceed ~500 K. Localized environments within the same region of the nebula must have been heated to temperatures in excess of 1000-1500 K to produce chondrules (Grossmas, MESS, 680) and CAIs (MacPherson et al., MESS, 746), either by transient events (Levy, MESS, 697) or by interactions with an energetic solar wind (Huss, EMP 40, 165). In dust rich regions, such heating events could produce a wide range in redox conditions depending upon the degree to which silicates were vaporized (Rubin et al. MESS, 488) and may have been responsible for exchange reactions between several different isotopic reservoirs (Thiemens, MESS, 899). Even for the more abundant, volatile elements, the ratios of NH_3/N_2 or CH_4/CO in comets, planets and satellites indicates the existence of higher pressure/temperature subnebulae where chemical reactions proceeded to completion and which mixed to variable extent with a lower temperature/pressure environment where such reactions were kinetically inhibited (Prinn and Fegley OEPSA, 78).

11. PARENT BODY PROCESSES - H. McSween: In the quest for a heat source for asteroids, ^{26}Al was discovered in ancient planetary material (Hutcheon et al., Nature 337, 238). Thermobarometric studies of ordinary (McSween and Patchen, Meteoritics 24, 219), enstatite (Fogel et al., GCA 53, 2735), and carbonaceous (Keck and Sears, GCA 51, 3013) chondrites constrained the conditions for metamorphism within asteroids. Radiogenic isotopic study of ordinary chondrites suggests that the duration of metamorphism was 10^8 years (Brannon and Podosek, PLPSC 18, 555). Tomeoka and Buseck (GCA 52, 1627) described the aqueous alteration of CI chondrites, and Grimm and McSween (Icarus 82, 244) presented thermal models for ice-bearing carbonaceous chondrite planetesimals. Space weathering processes may have altered S-asteroid regoliths to produce the observed reflection spectra (Bell and Keil, PLPSC 18, 573). There is evidence in shergottites for Martian weathering (Gooding et al., GCA 52, 909; Wright et al., GCA 52, 917). The effects of impacts on the parent bodies of aubrites (Keil et al., GCA 53, 3291) and ordinary chondrites (Sneyd et al., Meteoritics 23, 139) was documented. Discovery of a carbonaceous vein in an Antarctic ureilite indicates its parent object may have been a partly melted carbonaceous chondrite (Tomeoka and Takeda, GCA 54, 1475). A model for compaction of ureilite crystals (Walker and Agee, Meteoritics 23, 81) has implications for the thermal structure of the parent asteroid.

12. METEORITES FROM MARS - J. Longhi: Although the SNC (shergottites-nakhlites-Chassigny) meteorites seem to come from Mars, crystallization and shock ages remain ambiguous. Shergottites have young crystallization ages (<200 Ma) as opposed to 1.3 Ga for Nakhla and Chassigny (Jagoutz, GCA 53, 2429). Pyroxenes in Shergotty indicate a light-REE-depleted parent magma, but the soluble light-REE enriched phase suggested by isotope studies was not found (Lundberg et al., GCA 52, 2147). Modeling of Nakhla Sr and Pb trends to 180 Ma indicates consistency with isotope ration in shergottites (Jones, LPSC 19, 465). SNC parent magma compositions are low in Al_2O_3, similar to komatiites (Longhi and Pan, LPSC 19, 451). Incompatible element patterns in Nakhla and shergottites are distinct (Longhi, LPS 21, 716). Zoning patterns in Nakhla olivine suggest phenocryst equilibration prior to magma eruption (Treiman, LPSC 20, 273). Chassigny is 17x depleted in Ge, suggesting exposure to sulfur-bearing fluids (Malvin and Drake, GCA 51, 2117). Textures and carbon and oxygen isotopes indicate that calcite and Ca-sulphate in EETA79001 were preterrestrial (Gooding et al., GCA 52, 909; Wright et al., GCA 52, 917). Noble gas studies indicate that Martian gas (low $^{40}AR/^{36}Ar$, $\delta^{15}N$ near zero) is sited primarily in 10-100 m vesicles in EETA79001 glass (Wiens, EPSL 91, 55).

13. ISOTOPIC ANOMALIES - T. Swindle: A 25-year mystery indicated by isotopic anomalies in Xe was resolved by the identification of noble-gas-bearing carbonaceous grains including diamonds (Lewis et al., Nat 326, 160), silicon carbide (Bernatowicz et al., Nat 330, 128) and graphite (Amori et al., Nat 345, 238) that are probably interstellar. These grains, identified in several meteorite classes (Huss et al., LPS 21, 542), contain isotopically anomalous C, N, and Si (Anders, MESS 927; Zinner et al., GCA 53, 3273), whose compositions can be used to deduce nucleosynthetic sites. Isotopic anomalies in Zn (Loss and Lugmair, LPS 20, 588; Volkening and Papanastassiou, LPS 21, 1276) are smaller than expected (Lee, MESS, 1060), suggesting secondary processing. Meteorite grains exposed to the Sun have large concentrations of spallation noble gases, evidence that they were bombarded by a more active Sun or in a long-lived asteroidal regolith (Hohenberg et al., GCA 54, 2133; Padia and Rao, GCA 53, 1461; Wieler et al., GCA 53, 1441). More CAI with large fractionation effects have been discovered in Allende (Brigham et al., LPS 18, 129) and other meteorites (Ireland et al., LPS 20, 442). New studies of extinct nuclides include ^{107}Pd (Chen and Wasserburg, GCA 54, 1729), ^{146}Sm (Prinzhofer et el., ApJ 344, L81) and ^{53}Mn (Rotaru et al., LPS 21, 1037; Davis and Olsen, LPS 21, 258).

14. ORGANIC MATTER - E.L. Shock: Carbon, nitrogen and hydrogen isotopic studies revealed that the 'kerogen-like' material in meteorites consists of several components (Kerridge et al., GCA 51, 2527), and that amino acids in Murchison are similar to known interstellar organic materials (Epstein et al., Nat 326, 477). Polycyclic aromatic hydrocarbons are important constituents of the insoluble matter as shown by ^{13}C NMR (Cronin et al., GCA 51, 299), Raman (Allamandola et al., Sci 237, 56), and two-step laser mass spectrometry (Hahn et al., Sci 239, 1523; Zenobi et al., Sci 246, 1026). These data have led to a reappraisal of the synthetic pathways commonly used to explain the presence of organics in meteorites (Kerridge et al., Origins of Life 19, 561), and especially the Fischer-Tropsch reactions (Yuen et al., LPS 21, 1367; Wright and Gilmour, Nat 345, 110). Attention was focussed on the effect of parent-body aqueous alteration on meteorite organics (Cronin, ASR vol 9: No 2, 59; Shock and Schulte, Nat 343, 728), possible sources of analytical contamination and/or bias (Kerridge et al., GCA 52, 2251; Shock and Schulte, LPS 21, 1150), and delivery of meteorite organics to the Earth (Muhkin et al., Nat 340, 46; Anders, Nat 342, 255; Chyba, Nat 343, 129). Amphiphilic compounds were extracted from Murchison (Deamer and Pashley, Origins of Life 19, 21). Hydrocarbons were extracted from Murchison (Cronin, ASR vol 9: No 2, 59) and Antarctic meteorites (Naraoka et al., Chemical Letters 1988, 831) and inferred to be present in enstatite chondrites (Grady et al., EPSL 87, 293), and ordinary chondrites (Grady et al., Met 24, 147; Robert et al., GCA 51, 1787, and 1807).