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. COMETS

The level of activity during the period covered, July 1990 to June 1993, was comparable, if not higher than in the previous period. Work continued on interpretation and modeling of the data from the 1986 apparition of comet P/Halley. Many of the research results reported in Bamberg (IAU Colloquium No. 116) were transferred to text book level (Mason 1990, Huebner 1990). Space mission research continued with the Giotto extended mission and preparation of CRAF and Rosetta. CRAF was eventually canceled, putting more importance on international collaboration for Rosetta. New lines of research were opened with the discovery of activity of 2060 Chiron, improved ground based CCD observations of distant comets, the spectacular breakup of the comet Shoemaker-Levy 1993e, and the detection of trans-Neptunian planetary bodies - potential Kuiper belt members. An important review of cometary science has been written by Festou *et al.* (1993). It contains a very complete list of references of literature up to 1992, including proceedings and monographs. Many international meetings as well as sections of larger Symposia dealt with the subjects of Commission 15. Most important for the community the *Asteroids, Comets, Meteors* series continued with its meetings in Flagstaff, USA, June 24-28, 1991 and in Belgirate, Italy, June 14-18, 1993 (IAU Symposium 160). Information on meetings relevant to Commission 15, can be also found in the IAU Information Bulletins and/or in the Astronomy and Astrophysics Abstracts.

1. Nucleus: properties, origin, and evolution - H. U. Keller and W. J. Markiewicz

Possibly the most important outcome of the period covered is the formulation of what is still not understood about the nature of cometary nuclei. Cont' ued analysis of data from the last apparition of P/Halley and ground based observations of distant short perio. .mets show that nuclei are highly irregular in overall shape, and may be inhomogeneous in physical structure or composition, are highly porous, and have very low albedos. Most of their surface is not active. Whipple's icy conglomerate model of the nucleus was confirmed in its basic idea. Significant conceptual differences, however, are emerging in various models (Houpis 1991). In the model of Greenberg and Hage (1990) the individual sub-micron particles are described in detail by relating elemental abundances to those of interstellar dust. These authors also predict porosity to be at least 95 %. Keller (1990) advocates a model of a solid matrix (microstructure) with volatile ices filling the internal voids (icy dirt ball) - in a sense reversing Whipple's original model. Still lacking is quantification of the mass and size distribution of agglomerates making up the solid matrix. The question of the size distribution is crucial for understanding the activity of comets, the relations between comets and meteors, as well as the scenario of nucleus formation itself.

Giotto and Vega data were used to create ever more complex models of P/Halley's nucleus. Detailed cartographic models of P/Halley's topography were constructed by Stooke and Abergel (1991). Improvements beyond their model are limited by the lack of understanding P/Halley's rotation (see below). The study of P/Halley's rotational properties continued (Belton *et al.* 1991, Samarashinha and A'Hearn 1991). This complex problem important for the coma morphology as well as the nongravitational effects on the orbit is still not completely resolved. The irregular shape of the nucleus and the asymmetric outgassing are too complex to fully constrain models that try to describe the rotational, precessional and nutational motion. Effects of random jets on the spin state of P/Halley were considered by Julian (1990). Existing photometric and spectral data suggest a remarkable similarity between Trojan asteroids and cometary nuclei (Jewitt and Luu 1990). Modern CCD instruments have made it possible to observe with ground based telescopes the spectroscopic properties of nuclei of distant (inactive) comets (Luu 1993). Jewitt and Luu (1992a) developed a novel observational method in the submillimeter continuum. Whipple (1992) introduced a volatility index for comets. His study of many long and short period comets resulted in the same average values of volatility, and showed no correlation with usual orbital

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and physical parameters. This result suggests that active comets are basically alike regardless of their orbits or ages.

Laboratory studies of ices and ice/dust mixtures continued. The results of the KOSI (cometary simulations) project were reported in a special issue of Geophysical Research Letters (Grün *et al.* 1991). A review of sublimation experiments in USSR was written by Ibadinov *et al.* (1991). The cosmic-ray irradiation experiments have been reviewed by Strazzulla and Johnson (1991). Experiments with amorphous ices or ice mixtures have been reviewed by Klinger (1991).

A number of additional physical processes have been included in a new generation of thermal models of the nucleus. Porosity, heat transport by water vapor, chemical differentiation, amorphous - crystalline transition of the H_2O are some of the points discussed in this context (Fanale and Salvail 1990, Espinasse *et al.* 1991, Prialnik and Mekler 1991, Prialnik 1992). Similar models were calculated by Spohn and Benkhoff (1990) and applied to KOSI experiments resulting in estimates of various thermal diffusivities of a ice/dust porous mixture.

The restricted surface activity of comets continues to challenge our understanding of the surface composition, presence and formation of dust mantles, and the ways in which the dust component is agglomerated (glued) within the nucleus. The formation of dust mantles on nuclei was inferred from statistical analysis of nongravitational effects of short period comets (Rickman *et al.* 1991). Baratta *et al.* (1991) derive from photometry of P/Brorsen-Metcalf the existence of tiny grains of blue color with diameters < 0.1 μ. Their results supposedly support the existence of organic cometary crust. Sekanina (1993) analyzed the evolution of active sites as inferred from nongravitational perturbations of cometary orbits. The rôle of POM and CHON particles as cometary gluing agents was discussed by Boehnhardt *et al.* (1990). H_2CO rotational lines in mm range were predicted by (Bockelée-Morvan and Crovisier 1992) and detected by microwave observations in three different comets (Colom *et al.* 1992). Rickman *et al.* (1990) show by numerical simulations that the formation of stable dust mantles is possible for specific circumstances on parts of a cometary surface. Carusi *et al.* (1991) studied the last 47 orbits of P/d'Arrest (since 1678). They showed that the strength of nongravitational forces was stable and that the absolute brightness and the shape of the light curve have not changed during this period.

Cometary activity at large heliocentric distances received much attention. West *et al.* (1991) reported the observation of P/Halley's outburst at 14 AU, the farthest cometary outburst to date. An analysis and models are given by Sekanina *et al.* (1992), requiring CO as the volatile agent. Hughes (1991) summarized possible outburst mechanisms. Polymerization of HCN could also be a possible cause of cometary outbursts (Rettig *et al.* 1992). Wallis and Wickramasinghe (1991) draw an analogy between Triton's geysers and their "frozen sea" model of cometary outbursts. 2060 Chiron was shown to be a giant comet by photometric observations (Hartmann *et al.* 1990, West 1991). From submillimeter photometry the diameter of Chiron was constrained to be ≤300 km (Jewitt and Luu 1992b). Chiron's activity was reported to vary on time scales of hours (Luu and Jewitt 1990). Hahn and Bailey (1990) calculated past and future orbits of 2060 Chiron. They conclude that Chiron was likely a short period comet in the past and will be one in the future. CN emission from Chiron was detected by Bus *et al.* (1991). Interest in P/Halley's outburst and the cometary activity of 2060 Chiron gave rise to the *Workshop on the Activity of Distant Comets* (Huebner *et al.* 1993).

IAU Symposium No. 152, *Chaos, Resonance and Collective Dynamical Phenomena in the Solar System*, in Angra dos Reis, Brazil (15-19 July 1991) covered the new developments in the study of evolution of cometary orbits, the Oort cloud and related matters. Bailey (1992) concluded from a numerical study, that long-period comets with initially high-inclination (i~90°) orbits and moderately small perihelion (q < 2 AU) frequently become sun grazers. The mass involved in their destruction is an important source of interplanetary matter. The observed asymmetry in aphelia of new (long-period) comets is attributed to the motion of the solar system through its local galactic neighborhood (Brunini 1993). Revising data on orbits to include statistical effects of outbursts and nucleus splitting Kresák (1992) confirmed that there is no evidence that any of the recorded comets has a hyperbolic orbit (*i.e.* comes from interstellar space). Contrary to Whipple's nongravitational model Sekanina (1993) showed that the change in orbital period is not directly correlated with the sense of rotation of the nucleus. Asymmetry in the production rate relative to perihelion and the location of single jets influence the orbital period.

A review of the origin and evolution of the Oort cloud was written by Weismann (1990). Numerical studies of the formation of the Kuiper belt by scattering of comets by planets was reported by Ip and Fernández (1991). Abundance ratios of key gaseous molecular components of P/Halley were used to infer under what conditions this comet was formed (Engel *et al.* 1990). Carbon species could have originated from within the solar nebula, but ammonia must have come from outside. A surrounding molecular cloud is proposed as a possible source. Sublimation and reformation of icy grains in the primitive solar nebula are discussed by Lunine *et al.* (1991). It is shown that comets are likely to be made up of unprocessed grains. Growth of fluffy cometary nuclei by random accumulation of grains was studied by Donn (1991). The general aspects of cometary origin and relation to solar system cosmogony were reviewed in several chapters of *Protostars and Planets III* (Levy *et al.*, eds., The University of Arizona Press, 1993). The first detection of a potential member of the Kuiper belt, object $1992QB_1$, was reported by Jewitt and Luu (1993) and was followed by their discovery of a second, 1993 FW (IAU Circular No. 5730).

The possibility of observing line emission in OH, CN, and C_2 from cometesimals around millisecond pulsars as a means of detection of another planetary system was proposed by Chakrabarti and Krishna Swami (1992). Mitrofanov and Sagdeev (1990) have shown that gamma ray bursts from neutron stars could be accounted for by considering encounters with comets. Stern *et al.* (1990) explain the observation of water masers and complex molecules in envelopes of giant and super-giant stars in terms of an evaporating circumstellar comet disk. This model provides additional evidence for planetary systems about other stars.

2. Dust coma and tail - S. M. Larson

This period was punctuated by the Giotto flyby of P/Grigg-Skjellerup, the first Hubble Space Telescope comet observations, an outburst of P/Halley at 14 AU, the development of the coma and tail of 2060 Chiron, and the appearance of P/Swift-Tuttle.

The 1992 Giotto Extended mission to within 200 km of P/Grigg-Skjellerup on July 10 detected 3 meteoroid impacts indicating a dust mass distribution dominated by large particles (McDonnell *et al.* 1993). Modeling of nearly simultaneous ground based observations also indicated large particles as well as to provide additional dust parameters including a hemispherical emission pattern (Fulle *et al.* 1993).

Cometary observations with the Hubble Space Telescope started with Comet Levy (1990c) whose coma was characterized by expanding shells with the very low apparent velocity of 160 m/s (Weaver *et al.* 1992). Since that time, the dust comae of several other comets have been observed.

Observations at ESO showed that P/Halley underwent an outburst when at 14 AU from the sun. The expanding crescent-shaped dust coma was observed for several months, and could be modeled as a short-term emission from the sunlit side (Sekanina *et al.* 1992). The derived mass loss in this event was $\sim 10^{12}$ g, and the particles could have been driven by carbon monoxide to their 45 m/s terminal velocity, but the mass loading would have been enormous. Although there are several possibilities (*e.g.* Schmidt *et al.* 1993) the triggering mechanism may never be known.

The coma of 2060 Chiron has become more pronounced as it approaches perihelion (*e.g.* Luu and Jewitt 1993), and a tail was reported in 1992 (Larson and Marcialis 1992).

Dust trails for 8 periodic comets near perihelion, and others with no known parents, were identified on IRAF images (Sykes and Walker 1992). These features likely consist of large refractory particles.

The characteristic polarization-phase angle dependence of cometary dust, and a wavelength dependence of polarization at larger phase angles, observed in 13 comets by Chernova *et al.* (1993), was found to be consistent with large fluffy particles. The deviation from a 1/r radial profile of dust in 10 of 14 comets observed by Baum *et al.* (1992) was interpreted as evidence for grains fading with time. The particle size distribution has been modeled in several comets using a numerical inversion technique to fit observed isophotes and neck-line structures (Fulle 1992a, 1992b; Fulle *et al.* 1992, 1993). They show that the dust size distribution of dynamically newer comets tends to have a higher power index than for periodic comets.

P/Swift-Tuttle, the parent of the Perseid meteor stream, went through perihelion in 1992 and displayed spectacular dust jets (Yoshida *et al.* 1993) whose evolution was consistent with the one observed in 1862 (Sekanina 1981).

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3. Gas coma and photochemistry - M. C. Festou

The data collected during the spacecraft encounters with comet P/Halley were investigated in more detail. Geiss *et al.* (1991) using IMS-HIS data found that all ions observed in the 25-35 amu range could be explained as the result of the protonation of methanol, formaldehyde, hydrogen cyanide and hydrogen sulfide molecules. The IMS data were used by Boice *et al.* (1990) to infer the presence of an extended source of coma species and they derived an upper limit of the CH_4 production relative to water of 2%. The PICCA data revealed the presence of many sulfur-bearing ions (Marconi *et al.* 1991). Huntress *et al.* (1991) discussed the possibility that carbon suboxide could exist in comet P/Halley. Using TKS spectra Krasnopolsky and Tkachuk (1991) derived the NH and NH_2 productions and Krasnopolsky *et al.* (1991) studied the spatial distributions of CN and C_3. Krasnopolsky (1991) discussed the possible nature of the parents of C_3 and CN. Chaizy *et al.* (1991) have presented for the first time evidence of the presence of negative ions in the inner coma of P/Halley. The water production rate in P/Grigg-Skjellerup has been determined by Johnstone *et al.* (1993) from the JPA experiment data.

Jets of various coma species, including ions, have been found in comet P/Halley as well as in comets observed more recently. H_2O^+ and C_2 jets were studied by Formisano *et al.* (1991). Images of the H_2O^+ emission, an indicator of gas phase reactions with water molecules, were obtained by Disanti *et al.* (1990) at the time of the spacecraft encounters with P/Halley. Fabry-Perot observations by Scherb *et al.* (1990) can provide the velocities of these ions. Velocities of H_2O^+ ions were measured in comet Levy (1990v) by Rauer and Jockers (1993).

The structure of the CN jets was studied by Schulz (1991, 1992) and Schulz *et al.* (1993), who found that CN jets were evolving into CN shells. Column densities were derived by Schulz (1993). The jets and shells structures were also modeled by Kömle (1990). Klavetter and A'Hearn (1992) deduced from their images, which revealed the existence of CN jets in P/Halley, that the velocities of these jets exhibited a wide range of values and little evidence of acceleration. The connection between the C_2, CN, C_3 jets and active regions was studied by Jockers *et al.* (1993). The effect of solar activity on CN and C2 coma scales was investigated by Meredith *et al.* (1992).

Images of the L-α emission obtained of P/Halley from the Pioneer-Venus probe were analyzed by Smyth *et al.* (1991) using a comprehensive model of the kinematics and dynamics of the H coma. Images of the L-α coma at a time close to the spacecraft encounters were analyzed by McCoy *et al.* (1992). The morphology and characteristics of the H coma were reviewed by Shimizu (1991) and Hirao (1990). Combi and Feldman (1992) showed that the L-α observations of comet P/Giacobini-Zinner obtained with IUE in 1985 were fully compatible with an origin of the H atoms from the photodestruction of water and OH molecules.

Rickman *et al.* (1991) did a statistical study of nongravitational forces in short period comets in relation to their absolute brightness and orbital history. Spinrad (1991) measured center of light displacements in the comae of comet 1983 VII and P/T2, and Medvedev (1991) investigated the relationship between non gravitational effects and such shifts. Chernetenko (1991) found that the light shift in comet P/Encke did not depend on heliocentric distance.

The brightness of comets, closely related to the CN, C_2 and dust contents of their comae has been the object of many investigations. Kamél (1991) found that the absolute magnitude of P/Encke did not significantly vary since the discovery of the comet whereas Kresák and Kresáková (1990) found the opposite result in their more extensive study of the evolution of the absolute magnitude of comets. Svoren (1991) found that the decrease of the brightness of short period comets was linked to the comet orbital elements and indicated rather short orbital lifetimes. Roettger *et al.* (1990) found a clear correlation between gas production rates and visual magnitudes, although departures from this perfect behavior are frequent. Donnison (1990) investigated the properties of the distribution of comet magnitudes. Morris and Hanner (1992) have attempted for the first time to correlate the IR and visual light curves of comets. The brightness of the coma of P/Halley in 1910 was investigated by Schleicher and Bus (1991) who found the same 7.4 day period as was derived from photometric data collected in 1986. Howell *et al.* (1991) analyzing 1910 spectra of P/Halley found that gas and dust productions were slightly larger then than during the 1986 apparition.

Spectrophotometric observations of comets were interpreted in terms of gas production rates of radicals observed in the optical by De Almeida (1991), Sanwal and Rautela (1991), Schleicher *et al.* (1991)(comet Levy, 51 nights), Fink *et al.* (1991), Wyckoff *et al.* (1991a)(NH_2), Wyckoff *et al.* (1991b)(N depleted in P/Halley by about a factor of 6 relative to the solar composition), Landaberry *et al.* (1991), De Almeida (1992), Tegler *et al.*

(1992)(NH_2 in comet P/Brorsen-Metcalf), Ellis and Neff (1992), Beaver *et al.* (1990)(P/Giacobini-Zinner depleted in NH_2), Schleicher *et al.* (1990)(P/Halley, from Sept. 85 till June 86), Fink and DiSanti (1990)([O I] lines), Boehnhardt *et al.* (1990)(P/Temple 2), Jockers *et al.* (1993) and Vid'machenko *et al.* (1990)(P/Halley pre-perihelion). Spectrophotometric and in situ measurements that led to the determination of the composition of comets were discussed in Krankowsky (1991), isotopic ratios are presented by Vanysek (1991). The various water production rate evaluations were compared by Festou (1990a) who found them to be sometimes slightly discrepant. The size and homogeneity of the IUE data base allowed the intercomparison of UV spectra of comets and established that all comets look similar, except for their CO/water and dust/water production ratios (Festou 1990b).

Upper limits for the production of SO and SO_2 molecules (Kim and A'Hearn 1991) and SH (Kim and A'Hearn 1992) were derived from the interpretation of IUE spectra. The fluorescence of S_2 molecules was re-evaluated by Kim *et al.* (1990), which led to the determination of very low upper limits to the production of that species in many comets (Budzien and Feldman 1992). The origin of S_2 remains unknown. The IUE observations of comet Levy (1990c) revealed a short term variability of all emission features; the data were used to infer the velocity of the dust particles escaping from the nucleus (Feldman *et al.* 1992).

The existing reviews on the UV spectrum of comets have been updated by Feldman (1990,1991a) and the composition of volatiles was derived (Feldman 1991b). Budzien and Feldman (1991) present IUE observations of comet 1983 VII that indicate the presence of OH prompt emission longward of 3000 Å. Krishna Swamy and Tarafdar (1993) studied the rotational distribution of CS. First observations of the 900-1200 Å region was accomplished for comet Austin (1989c1) by Green *et al.* (1991) and for comet Levy (1990c) by Feldman *et al.* (1991). The optically thin H I L-β line (blended with an oxygen line) was observed for the first time, and upper limits for the production of some rare gases were obtained. Upper limits of He and Ar productions were derived by Stern *et al.* (1992) from comet Austin data. O'Dell *et al.* (1991) recorded the UV spectrum of comet P/Brorsen-Metcalf (1989o) in which they found numerous new lines or bands, most of which are CO_2^+ emissions. Valk *et al.* (1992) performed similar work with observations of comet Austin (1989c1). Measurements of the H_2O^+/CO^+-ratio have been obtained for comets Halley, Bradfield and Wilson (Lutz *et al.* 1993) and Prasad *et al.* 1991). The values were consistent with photoionization of H_2O and CO. However ratios of other species were found to disagree with theoretical predictions. Mamadov (1990) claimed the discovery of water lines in spectra of comet Okazaki-Levy-Rudenko (1989 XIX). Esipov *et al.* (1991) claim they have detected new bands of CN and C_2 in the near-IR region. The investigation of 13 CN spectra of comet P/Halley taken at high resolution led Jaworski and Tatum (1991) to a new determination of the ratio $^{12}C/^{13}C = 89 \pm 17$. While the observation of CO^+ emission in comet P/Schwassmann-Wachmann 1 by Cochran *et al.* (1991) was not surprising, that of CN by Cochran and Cochran (1991) was quite unexpected and is still unexplained. A possible detection of a CO^+ tail of that comet on CCD images was reported by Jockers *et al.* (1992).

The 3.4 micron feature has been given much attention since its discovery in P/Halley. It was imaged by Klavetter and Hoban (1992). The spectrum near 3.28 micron was studied by Davies *et al.* (1991). Hoban *et al.* (1991) tentatively attributed the 3.52 micron band to methanol emission, an identification that is supported by calculations by Reuter (1992) of the fluorescence of formaldehyde in that region of the spectrum. The nature of the organic compounds in comets is discussed by Delsemme (1991). Brooke *et al.* (1991) suggest that organics are present in all comets at the same level relative to water. Observations of comet Austin (1989c1) by DiSanti *et al.* (1992) placed a significantly lower upper limit for the production of OCS in comets than had been previously obtained from P/Halley . These molecules cannot be a significant source of sulfur atoms in comets.

Hu *et al.* (1991) determined the theoretical velocity profiles of parent molecules. Larson *et al.* (1991) measured the velocity profiles of water molecules in comet Wilson (1987 VII). Discussions of the IR and radio observations of comets are found in Weaver *et al.* (1991) and Crovisier and Schloerb (1991), respectively. Encrenaz and Knacke (1991) discussed the presence of carbonaceous materials in comets. Radio interferometric observations were covered by de Pater *et al.* (1991). Snyder (1992) presented the parent molecules that have been safely identified in comets.

The stable H_2S (hydrogen sulfide) and CH_3OH (methanol) molecules were discovered by Bockelée-Morvan *et al.* (1990a, 1991) in comets Austin (1989c1) and Levy (1990c). Observations of H_2S and searches for other parent molecules are also presented in Crovisier *et al.* (1991) for comets Austin (1989c1) and Levy (1990c).

Additional millimeter observations of various comets were presented by Colom *et al.* (1992), Crovisier *et al.* (1993) and Snyder *et al.* (1990). These data allow the investigation of the kinematics of parent molecules in comet comae and in general suggest a strong sunward ejection.

The observation of an occultation of a point like radio source by comet Okazaki-Levy-Rudenko (1989 XIX) allowed Crovisier *et al.* (1992) to study in detail the excitation mechanism that is used for observations of the OH radio lines. OH data collected at Nançay have been analyzed by Bockelée-Morvan *et al.* (1990b). From observations of the 1667 MHz line, Tacconi-Garman *et al.* (1990) found that the OH coma of various comets was highly asymmetric.

Formation of water dimers in the inner coma was investigated theoretically by Crifo and Slanina (1991). Crifo (1992) described a new coma model which includes homogeneous and ion-induced water recondensation. A complete investigation of the chemistry in comet P/Temple 2 was performed by Huebner *et al.* (1992). The structure of the coma of comets was reviewed by A'Hearn and Festou (1990). Ionization mechanisms that may be at work in comets were investigated by Ibadov (1991). The ion enhancement observed at the ionopause of P/Halley was modeled by Keller and Cravens (1990).

4. Plasma - H. Rauer

A number of books containing reviews on cometary plasma has been published in the past years. Reviews published in *Comets in the Post-Halley Era* (Newburn *et al.* eds. 1991) address the interaction of the solar wind with the comet, particularly the magnetic field structure, waves and instabilities and the ion population. These points are also addressed in *Comet Halley, Investigations, Results, Interpretations* (Mason ed. 1990) with detailed overviews on the results obtained by the various spacecraft experiments at comet Halley encounter. Ip and Axford (1990) discussed in detail the processes associated with ions in the vicinity of comets, like large-scale processes, plasma waves and ion acceleration. Many interesting aspects are covered in the proceedings of the 1989 AGU Chapman conference, *Cometary Plasma Processes* (Johnstone ed. 1991). Recent results of cometary observations of ions have been presented at a workshop, *Observations of Recent Comets*, held in 1990 (Huebner ed. 1990) and at *Asteroids, Comets, Meteors*, in 1991 (Harris and Bowell eds. 1992), and in 1993.

Observations of large scale structures in plasma tails have also been obtained. An asymmetric ion ray enhancement in comet Halley in December 1985 was described by Watanbe *et al.* (1990). Tail rays in comet Bennet 1970 were described by Miller (1992) who suggested magnetically channeled outflow for their creation mechanism. Moore (1991) studied the closure rates of tail rays, compared them to predictions of existing models of ray formation and concluded that non of the models considered can explain all aspects of the observed phenomena. Delva *et al.* (1991) correlated sector boundaries in the solar wind measured by the Vega spacecraft with disconnection events seen in the tail of comet Halley. A correlation of only 50 % was found; in half of the cases the sector boundary had no effect on the plasma tail.

Further measurements of ion velocities have been made. Herbig (1990) measured gas and ion velocities in the inner coma region. Rauer and Jockers (1993) combined velocity measurements using a Fabry-Perot etalon with imaging of comet Levy 1990c1. The 2-D distribution of the velocity field was obtained for the first time. It was possible to show that structures seen in the tail of comet Levy move due to particle motion. Determinations of ion production rates from ground generally gave values less then expected from theory.

Data obtained at the encounters of the ICE spacecraft with comet Giacobini-Zinner and of Giotto and the Vega spacecraft with comet Halley continued to be evaluated and updated. First results on the encounter of Giotto with the weak comet Grigg-Skjellerup have also been reported. The plasma parameters at Halley's bow shock were re-analyzed and data of the outbound path have been presented for the first time (Coates *et al.* (1990) and Amata *et al.* (1991)). The magnetic field observations obtained by Giotto at the outbound bow shock of comet Halley showed a new type of shock transition called a "draping shock" (Neubauer *et al.* 1990). A comparison of JPA data with data obtained by the IMS experiment was made by Neugebauer *et al.* (1992).

Results on the energization and pitch-angle scattering at comets Halley and Giacobini-Zinner have also been published and compared with models (Tan *et al.* 1990, Neugebauer *et al.* 1990, McKenna-Lawlor 1990, Staines *et al.* 1991a, Kecskeméty and Cravens 1992 and Tan *et al.* 1993a). Pick-up water group ions were also detected at the most recent comet encounter, Giotto's visit to comet Grigg-Skjellerup (Johnstone *et al.* 1993 and Coates *et al.* 1993). The magnetometer data (Neubauer *et al.* 1993) showed the crossing of a bow shock on the outbound and of a bow wave on the inbound path at this weakly outgassing comet. Waves produced by ion pick-up showed much simpler waveforms than found at comet Halley. Data from the EPONA experiment (McKenna-Lawlor (1993)) showed periodic variations in the ion intensities, indicating a strong coupling to the magnetic field close to the nucleus. Observations of plasma waves at comets Halley and Giacobini-Zinner have been presented by Mazelle *et al.* (1991), Staines *et al.* (1991b), Moses *et al.* (1992) and Tan *et al.* (1993b).

A reevaluation of the data obtained by the HERS experiment at comet Halley has been presented by Neugebauer *et al.* (1991) showing disagreement with predictions of models. The data were discussed together with the results of the HIS experiment by Goldstein *et al.* (1992). Heavy ions at large distances ($8 \cdot 10^6$ kilometers) from the nucleus were found by analysis of the EPONA data (Erdös *et al.* 1991). The effect of solar wind charge exchange in the cometary coma has been discussed by Fuselier *et al.* (1991) and Wallis (1991).

The spacecraft data initiated a large number of theoretical investigations. A gasdynamic model, describing the interaction of the solar wind with a comet was given by Baranov and Lebedev (1993). The authors found good agreement of their model with the spacecraft data of comet Halley in the outer shock layer and in the description of the shear layer, identified with the heavy ion mantle found by the experiments. Schmidt and Wegmann (1991) gave an overview on the results of a 3-D MHD approach of the solar wind interaction and the comparison with spacecraft data. A parametric study of the interaction has been performed by Russell *et al.* (1991a).

Pitch-angle scattering of cometary ions and the effect on the cometary environment was discussed in many papers. Flammer *et al.* (1991 and 1992) presented a self-consistent 1-D model to study particles and fields kinetically. The model is applicable to the unshocked region upstream of the comet. Both the ring and shell like ion velocity distribution and the role of pitch-angle scattering were considered. A stability analysis of the ion shell distribution was given by Yoon (1990). Yoon and Ziebell (1991) studied the dependence of pitch-angle diffusion on the injection angle α. For the quasi parallel case pitch angle diffusion remained small, for the quasi perpendicular case the diffusion rate increased. This was in general also found by Gary *et al.* (1991) in agreement with observations at comet Halley. The scattering was also found to be almost independent of the solar wind/cometary ion speed and to increase as the square root of the injection rate. Pitch-angle scattering into a mono- and bi-spherical distribution was discussed by Miller *et al.* (1991b) and the combined effect of pitch-angle and energy diffusion was studied by Ye and Cravens (1991) and Ye *et al.* (1993). As expected they found pitch-angle diffusion to occur much faster. The thermalisation of an isotropic spherical shell distribution was discussed by Yoon (1992). Huddleston *et al.* (1991) had studied the pick-up process at comet Halley to explain the measured development of the implanted ion distribution. They also compared the ion energy distribution obtained by their model with results obtained by Giotto (Huddleston *et al.* 1992).

A number of publications showed various aspects of waves and instabilities generated in the cometary environment (Miller *et al.* 1991a, Lee and Gary 1991, Kotelnikov *et al.* 1991, and in Johnstone ed. 1991). Khabibrakhmanov *et al.* (1991), Ip and McKenzie (1991) and Zank (1990) investigated cometary bow shocks. A review on the formation of cometary shocks was given by Omidi and Winske (1991).

The stability of the ionopause was also investigated. McKenzie *et al.* (1990) extended their analysis by including finite plasma pressure in addition to the effect of ion-neutral friction. Another stability analysis taking into account the effect of ion-neutral drag was given by Daohan and Linzhong (1992). The flow around the diamagnetic cavity was discussed by Isrealevich *et al.* (1992) by adding centrifugal force to the momentum balance to explain the magnetic field structure observed. The existence of energetic ions in the inner coma has been addressed by Gurgiolo and Winningham (1990) and Ip (1992), by suggesting influences of sudden movements of the contact surface and of a magnetic neutral line. The formation of an ion density enhancement at the diamagnetic cavity found by the Giotto measurements was studied by Keller and Cravens (1990).

Wang (1991) investigated mechanisms to produce the large-scale structures found in cometary plasma tails in ground-based observations. He suggested the formation of some of these structures due to streaming sausage, kink and tearing instabilities. Russell *et al.* (1991b) studied the existence of mirror waves at comet Halley which might become visible as rays under favorable viewing conditions.

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Comet Halley, Investigations, Results, Interpretations. Volume 1: Organization, Plasma, Gas. (Mason, J.W. Ed.), 295 pp.; *Volume 2: Dust, Nucleus, Evolution.* (Mason, J. and P. Moore Eds.), 275 pp. 1990. Ellis Horwood Library, Chichester. (*CHIRI*)

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1. Asteroid Sizes and Masses

The mass of 1 Ceres was redetermined By Williams (1992) through careful analysis of the Ceres-induced perturbations undergone by the smaller asteroid 348 May. A similar result has been obtained by Goffin (1991) from the motion of 203 Pompeja, while Sitarski and Todorovic-Juchniewicz (1992) combined the data from both asteroids for the same purpose. The mass of 704 Interamnia has been derived by Landgraf (1992) from the perturbations of 993 Moultona. In order to extend the scope of this method, applied so far only to the few largest asteroids, Kuzmanoski and Knezevic (1993) compiled an extensive list of close encounters between large asteroids and all the other known ones that will take place in the next 50 years.

Two stellar occultations by large asteroids (2 Pallas and 4 Vesta) were well observed through organized *ad hoc* campaigns (Millis *et al.* 1990, Dunham *et al.* 1990). They led to new, more accurate estimates for the sizes, shapes and densities of these bodies, leading to important reassessments and calibrations of the other methods which are more frequently available for the same purposes. From the occultation of the star SAO 190531, Kissling *et al.* (1991) derived a diameter of 9 Metis in a good agreement with radiometric and polarimetric results.

Using albedos derived from the IRAS spacecraft survey of infrared sources, Cellino *et al.* (1991) analyzed the distribution of asteroid sizes taking into account the main observational selection effects. They found clear deviations from a power-law size distribution, both for the overall asteroid population and for several subsamples, sorted according to orbital semimajor axis and family membership.

2. Photometry, Shapes, Rotations

Lightcurve photometry is still a very active area of asteroid astronomy. Lightcurve observations are continuously published in the Minor Planet Bulletin as well as in other journals. A partial list of papers presenting lightcurves of individual or groups of asteroids includes Hoffmann and Geyer (1990), Velichko *et al.* (1990), Magnusson and Lagerkvist (1991), Dahlgren *et al.* (1991), Erikson *et al.* (1991), Belskaya and Dovgopol (1992), Dovgopol and Lisina (1992), Dovgopol *et al.* (1992), Lagerkvist *et al.* (1992), Dotto *et al.* (1992) and Wisniewski (1992). Other papers, such as Michalowski and Velichko (1990), Michalowski *et al.* (1991), Kristensen (1991), Michalowski (1992) and Kwiatkowski and Michalowski (1992), have presented lightcurves together with an analysis of the inferred shapes and/or poles of the corresponding objects. Ostro and Wisniewski (1992) compared lightcurve and radar data relevant for the shape of 1917 Cuyo.

In the last three years a particular effort has been focused on the targets of current or planned space missions, such as 951 Gaspra (Di Martino *et al.* 1990, Wisniewski *et al.* 1993) and 243 Ida (Gonano-Beurer *et al.* 1992), in order to compare lightcurve-derived physical properties with high-resolution imaging data. Photometric studies of individual asteroids can also indicate heterogeneities of composition and texture of the surface, such as indicated by phase relation and color variations for 51 Nemausa (Gammelgaard and Kristensen 1991, Kristensen and Gammelgaard 1993). Analyses of the data set contained in the *Asteroid Photometric Catalogue* have been presented by Magnusson and Lagerkvist (1990) and Magnusson (1991), who aimed at detecting the presence of albedo variegation on asteroid surfaces by analyzing the Fourier expansions of composite lightcurves. CCD photometry of selected asteroids centered on wavelengths of common emission features in comet spectra was applied by Rajamohan and Bhargavi (1992) to check for possible cometary activity features. Shkuratov and Muinonen (1992) developed a model to interpret asteroid photometry and polarimetry data in terms of shadowing and coherent backscattering effects.

Since currently the available lightcurve data base includes several hundreds of bodies, the emphasis of current research is shifting from studies of individual asteroids to general surveys of large samples of objects. In some cases, these surveys concerned the general asteroid population (Harris *et al.* 1992), but increasingly they are being designed to provide information on some subset of objects sharing some common property. For example, the "photometric geodesy" program of Weidenschilling *et al.* (1990) has focused on a number of large main-belt asteroids, with the aim of deriving accurate shape and polar direction estimates in addition to rotation periods, in order to assess how closely these objects match the axisymmetric or triaxial ellipsoidal equilibrium figures produced by the interplay of rotation and self-gravity (Drummond *et al.* 1991).

Another category of interesting bodies, which were under-represented in the observed sample until recently, are the outer-belt and Trojan asteroids. For these objects, an important research issue is whether they are genetically or compositionally related to comets (Hartmann and Tholen 1990). Following an earlier suggestion that distant asteroids may be more elongated than main belt objects, Di Martino *et al.* (1992) and Binzel and Sauter (1992) have obtained more data on distant asteroids. The newer data alone fail to show significantly greater elongations, although better statistical confirmation is needed.

The extension of the available data set is also important for small asteroids. Recent surveys aimed at these bodies (Wisniewski 1991, Binzel *et al.* 1992, Barucci *et al.* 1992a) have confirmed that these bodies have in general irregular, fragment-like shapes, and that there is a clear trend toward increasing spin rates for decreasing sizes, in agreement with theoretical predictions based on collisional evolution models (Farinella *et al.* 1992c). Hopefully, observations of km-sized bodies in the main belt will soon allow a meaningful comparison between the rotational properties of main-belt and near-Earth asteroids.

Theoretical studies of lightcurve inversion methods to derive poles and shapes have continued (Kaasalainen *et al.* 1992a,b; Kristensen 1992a,b). An important task now is that of obtaining a large enough sample of asteroid polar directions to assess whether their distribution is isotropic (*i.e.* randomized by precessional and collisional processes), or if there is some preferential clustering (*e.g.* about the pole of the ecliptic), that may be reminiscent of the asteroid accretion phase (Erikson and Magnusson 1993).

3. Radar, Radiometry, Polarimetry, Interferometry

In the last few years several observational techniques aimed at asteroids have been renewed and refined, providing a wealth of new information on the physical properties of these bodies and the composition and textures of their surfaces. The most outstanding example is probably the radar technique. Thanks to the availability of the large Goldstone and Arecibo antennas, the group led by S.J. Ostro has shown that radar data are not only extremely valuable for astrometry and orbit determination (Ostro *et al.* 1991a, Yeomans *et al.* 1992), but can also provide fairly accurate global shape estimates for the target asteroids. Some near-Earth objects (1672 Ivar and in particular 1989 PB, later named 4769 Castalia) clearly displayed bifurcated shapes hinting at a contact or quasi-contact binary structure (Ostro *et al.* 1990a, 1990b). For another body, 1986 DA, the very high radar reflectivity suggests a metal-rich composition (Ostro *et al.* 1991b).

Other techniques successfully applied to study asteroid physical properties include millimeter and submillimeter radiometry, used by Redman *et al.* (1992) to investigate the thermal behavior and the shape of 4 Vesta; speckle interferometry, applied again to 4 Vesta by Tsvetkova *et al.* (1991) to gather new shape and size data; and polarimetry, used both by the latter authors to estimate the contribution of albedo features to Vesta's lightcurve and by Chernova *et al.* (1993) to compare asteroid surfaces with dust particles emitted by comets. A search for rotational variations in the optical polarization of light coming from asteroids has been performed by Broglia and Manara (1990, 1992) first for 3 Juno and 7 Iris and then for 16 Psyche. An extensive campaign of polarimetric observations has been carried out on CMEU-type asteroids by Belskaya *et al.* (1991), who showed the possible different content of metal of different M-type objects.

4. Binaries and Families

While still not proven the case for the existence of binary asteroids was strengthened by radar observations of 1989 PB (Ostro *et al.* 1990b). Stern and Barker (1992) have conducted a further search for binaries among main belt asteroids. Their negative results may be due mainly to the limitations of the observational techniques available for searching satellites there.

At the same time a number of studies have addressed in detail the dynamical stability of these systems and the most important evolution mechanisms affecting them, including solar and Jovian perturbations, close encounters and collisions with passing asteroids and with planets (Chauvineau and Mignard 1990a, 1990b, 1990c; Chauvineau *et al.* 1991; Farinella 1992). The formation of doublet craters on Earth by collision of binary asteroids has been modeled by Melosh and Stansberry (1991). The possible existence of debris and dust particles around main-belt asteroids, which could pose a hazard for encountering spacecraft, has been investigated by Burns and Hamilton (1992) and Hamilton and Burns (1992). Orbital dynamics about a triaxial primary is complex, and numerical simulations on this problem have been carried out by German and Friedlander (1991).

Significant progress has been achieved in the last three years in studies concerning asteroid families. Williams (1992a) has published the results of his "initial search" for asteroid families, carried out on a sample of about 3000 objects (including both numbered and PLS asteroids) and showing a wide variety of family morphologies, including some peculiar, strongly non-isotropic structures (Williams 1991). The relationship to families of the Galileo target asteroids Gaspra and Ida was discussed by Williams (1992b). While Williams' search was based on human-eye pattern recognition in the proper element space, in recent years a number of automated clustering techniques have become available, leading to more objective and repeatable family identification procedures.

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Zappalà *et al.* (1990) applied their "hierarchical clustering" method to a sample of 4200 proper element triplets derived by Milani and Knezevic (1990), and submitted the detected grouping to rigorous tests for statistical significance and robustness vs. (small) errors in the proper elements. The same proper elements sample was analyzed independently by Bendjoya *et al.* (1991), who used the "wavelet analysis" method. Although based on very different principles, this method yielded family memberships in fair agreement with those found by Zappalà *et al.* (1990). Another automated search was performed by Lindblad (1992) through the "D-criterion", and again the resulting list of most reliable families was similar to those found in the papers quoted above. The work of the Italian and French groups was later reviewed and reassessed by Milani *et al.* (1992), Bendjoya and Cellino (1992), Zappalà and Cellino (1992) and Bendjoya *et al.* (1993). In the latter paper, the two clustering methods were successfully applied to recover "artificial families" generated numerically by exploding asteroids overlapping different backgrounds of field objects. A comparison with Williams' results was carried out by Zappalà *et al.* (1992) who concluded that the main remaining discrepancies mostly involve the many families identified by Williams with a small number (<10) of members - hence least significant from the statistical point of view. To provide a simple tool to distinguish among families with differing degrees of significance and reliability, Farinella *et al.* (1992a) proposed the adoption of a new nomenclature. Williams (1992c) has discussed in some detail the different effects bearing on the reliability of families found with his and other techniques.

5. Spectra and Compositions

As with lightcurves, a particular effort has been made to investigate by spectroscopic observations the physical and chemical peculiarities of the outer-belt asteroids. In particular their possible relationship to comet nuclei has been studied with a variety of different techniques. CCD spectra of 32 Trojans allowed Jewitt and Luu (1990) to infer a remarkable similarity between Trojans and the comet nuclei. Vilas and McFadden (1992) performed a search for weak features in the reflectance spectra on a set of 35 asteroids. One of their main results is that the Trojan D-class asteroids show no clear absorption features, implying that aqueous alteration did not operate at that heliocentric distance. Smith *et al.* (1992) performed JHK photometry of selected Trojan and Hilda asteroids. They found that leading Trojans and Hildas show similar and homogeneous colors, while trailing Trojans appear more heterogeneous.

Several papers have addressed the problem of the composition of the (presumably) "primitive" asteroids, namely those belonging to the C, D, P, and G taxonomic classes. In particular the presence or absence of water was investigated in detail. Jones *et al.* (1990) presented an extensive laboratory and telescopic research on water distribution among the low-albedo outer-belt asteroids. Their main conclusion is that the C class is not a primitive group in the mineralogical sense, although its anhydrous members appear little altered. Coupled with the apparently anhydrous P and D surfaces, this fact points to an original outer-belt asteroid composition of anhydrous silicates, water ice, and complex organic material. Vilas *et al.* (1993) have identified a 0.43 micron absorption feature in 12 high-resolution UV/visible spectra of asteroids of the C, P and G classes, indicating an aqueous alteration. The largest asteroid, 1 Ceres, has been the target of searches for water. King *et al.* (1992) obtained spectra of this asteroid to be compared with theoretical calculations and laboratory measurements. They suggested that an ammoniated phyllosilicate is present on the surface of Ceres, rather than water frost as it had been reported previously. On the other hand, A'Hearn and Feldman (1992) performed long-exposure IUE spectra of the region around Ceres, searching for escaping OH as a result of the photodissociation of atmospheric water vapor. The amount of OH found close to the northern limb is consistent with a polar cap, which is replenished during winter and dissipates in summer.

4 Vesta has been studied by Festou *et al.* (1991) through visual and ultraviolet observations from the IUE satellite, with the aim of developing a self-consistent picture of that large asteroid.

Fitzsimmons *et al.* (1990) discovered three broad absorption features (at 416, 441 and 515 nm) in the reflectance spectrum of the outer-belt asteroids 1269 Rollandia and 279 Thule. Cruikshank *et al.* (1991b) identified cyano-group containing molecules in the very dark solids of the surfaces of a few D-class asteroids, the dust of some comets, the low-albedo hemisphere of Iapetus, and the rings of Uranus. The occurrence of this band may establish a link between outer solar system and interstellar materials. Grundy and Fink (1992) obtained high quality CCD spectra of Deimos, showing that its very red slope matches those of D- rather than C-type asteroids. On other hand, McFadden *et al.* (1993) showed that the dynamically chaotic Earth-crossing object 2201 Oljato

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has a fairly high albedo and a spectrum more typical for an inner-belt asteroid than for an extinct or dormant comet.

Stephens and Gustafson (1991) presented laboratory measurements of bi-directional reflectances from particle/ice mixtures representing "dirty" ice surfaces on atmosphereless solar system bodies. The differences found between their samples and solar system bodies may reflect different physical processes during mantle formation as well as differences in chemistry of silicate and carbonaceous materials.

A newly discovered distant asteroid, 5145 Pholus (1992 AD), has shown some very peculiar features. In particular it displays a reflection spectrum having a red slope much steeper than that of any other atmosphereless object. No absorption or emission feature has been detected. The interpretations given by several authors (Fink *et al.* 1992, Mueller *et al.* 1992, Binzel 1992, Hoffmann *et al.* 1993) are generally in good agreement, and indicate an association of exposed organics that are purer or more pristine than that found on the surfaces of C, P, D asteroids and comets. Davies *et al.* (1993) also suggested the presence of surface ices mixed with complex organic compounds.

A new method to detect mass loss from near-Earth asteroids has been presented by Luu and Jewitt (1992), using high-resolution surface photometry. The negative result obtained so far is probably due to the low expected rates of activity and to the small sizes of these bodies.

An extensive search for silicate minerals has been performed by Shestopalov *et al.* (1990). They concluded that the silicate minerals of some asteroids contain iron-rich and calcium pyroxenes. Hiroi and Takeda (1990) applied a model for investigating mineral assemblages in asteroidal surfaces, based on theoretical studies of spectral reflectance of olivine, pyroxene and their mixture, to show that the properties of 29 Amphitrite can be reproduced by a mineral assemblage of primitive achondrites.

6. Origin and Collisional Evolution

The problem of the origin of asteroids presents a complex mixture of dynamical, cosmochemical and cosmogonical puzzles. It has been attacked from a number of different starting points. Lecar *et al.* (1992) and Soper *et al.* (1992) tried to explain the current distribution of the asteroids in the outer portion of the belt and the lack of long-lived bodies between Jupiter and Saturn by investigating the dynamical mechanisms that may have depleted the solar system from the original population of minor bodies. Hartmann (1990) reviewed the evidence for an early intense bombardment from dark, carbon-rich planetesimals in the inner solar system. Grimm and McSween (1993) modeled the heating of primordial asteroids by the short-lived Al-26 isotope, showing that this provides a plausible alternative to the other often mentioned explanation for the partial differentiation of primordial asteroids via electromagnetic induction. The formation of metallic cores inside differentiating asteroids was modeled by Taylor (1992) and Haack and Scott (1992). Wetherill (1992) explored a new model for the formation of asteroids, in which the current belt results from the collisional and dynamical interaction of a number of primordial lunar-sized bodies, later lost from the system due to mutual perturbations into resonances. Safronov and Ziglina (1991) investigated the reasons for the absence of an ordinary planet in the asteroid zone, concluding that the combined action of three possible mechanisms increasing relative velocities and removing material should be taken into account. From the current abundance of metal-rich bodies, Hughes (1991) estimated that the largest bodies that ever existed in the asteroid belt had diameters of around 8600 km. The origin of Trojan asteroids has been investigated by Ruskol (1990).

Collisions - in particular those which catastrophically shatter the target objects - represent the most important process currently causing the asteroid population to evolve. Farinella and Davis (1992) have performed a detailed quantitative study on asteroid collision probabilities and impact velocities, and how these quantities depend on orbital parameters and family membership. The study of asteroid collisional evolution requires as an essential prerequisite a reliable model of how asteroid-sized bodies respond to energetic collisions, derived by scaling from laboratory experiments (Housen and Holsapple 1990, Housen *et al.* 1991) and from numerical modeling work (Cellino *et al.* 1990). Melosh *et al.* (1992) and Asphaug and Melosh (1993) have been developing complex hydrodynamical algorithms, both in two and three dimensions, for this work. Based on simple scaling relationships, a quantitative study then becomes possible of how the size and spin rate distributions of a primordial population of asteroidal bodies may have evolved into the current one (Farinella *et al.* 1992c).

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However, extending the experimental data base on the outcomes of hypervelocity impacts is still a high-priority task. After the pioneering work carried out in the '70s and '80s, a refinement of the experimental techniques is now leading to exploring complex (albeit crucial for asteroid applications) issues such as the velocity distribution of fragments (Nakamura and Fujiwara 1991, Nakamura *et al.* 1992, Takagi *et al.* 1992), the effects of pre-fractured targets (Ryan *et al.* 1991), the rotation of fragments (Nakamura *et al.* 1992), the melting, vaporization and energy partitioning effects (Smither and Ahrens 1992), the angular momentum transfer in oblique impacts (Yanagisawa *et al.* 1991), the jetting of fragments about preferential planes and directions (Martelli *et al.* 1993).

7. Gaspra

(951) Gaspra has become the first asteroid subjected to close-up examination, by the space probe Galileo on 29 October 1991. These data and a first analysis have been presented by Belton *et al.* (1992). Pre-Galileo photometric observations of Gaspra had been performed by Di Martino *et al.* (1990) and Goldader *et al.* (1991), the latter authors deriving also an infrared reflectance spectrum. An extensive observational campaign to obtain Gaspra lightcurves was carried out prior to the encounter, as reported by Wisniewski *et al.* (1993). The shape, rotation rate and polar axis derived from these observations were presented by Magnusson *et al.* (1992). Barucci *et al.* (1992b) showed the pre-encounter shape models, obtained with different lightcurve inversion methods, are in agreement with the first Galileo image. Cartography techniques for asteroids and other small bodies imaged at low resolution were developed by Stooke (1992).

Estimates of the collisional lifetime and the surface evolution of Gaspra were obtained, before the encounter, by Namiki and Binzel (1991) and Farinella *et al.* (1992b). Both papers predicted a likely age of Gaspra on the order of several times 10^8 yr, a result consistent with the spacecraft observations. The possibility (unconfirmed by Galileo images) of finding small satellites around Gaspra was discussed by Van Flandern (1992). Williams (1992) analyzed the relationship of Gaspra to the populous Flora family.

8. Asteroids vs. Meteorites

Significant progress is being made in one of the most important issues in planetary science: the relationships between asteroid and meteorites and the identification of meteorite sources in the solar system. The dynamical side of the problem has been addressed by Froeschlé and Scholl (1991), Knezevic *et al.* (1991), Scholl and Froeschlé (1991) and Dahlgren *et al.* (1992), who studied the locations and effects of mean motion and secular resonances. Farinella *et al.* (1993a, 1993b) showed that both types of resonances provide efficient dynamical routes to deliver fragments of main-belt asteroids to Earth-crossing orbits. A clear example of this has been identified by Binzel and Xu (1992), whose spectroscopic observations of a a number of small Vesta family members, extending to the vicinity of the 3:1 mean motion resonance, showed the striking similarity of these objects to the basaltic achondrite meteorites. This finding is remarkable in that it provides strong evidence that collisional processes are capable of transporting debris from Vesta, which is far from any of the orbital resonance "escape hatches", to Earth-crossing orbits.

The comparison of asteroid and meteorite spectra has been carried out in a more extensive way than had been done previously (McFadden and Chamberlin 1992), including principal analysis classification of both data samples (Britt *et al.* 1992). The genetic implications of these comparisons have been carefully assessed (Fanale *et al.* 1992), taking into account the effects of a number of possible thermal and collisional processes leading to alterations of the spectral features of asteroid surfaces (Clark *et al.* 1992). In particular, these processes are important to assess whether some main-belt asteroids for which visible and near-infrared spectra are available are plausible candidate parent bodies for the ordinary chondrites, the most common meteorite class (Keil *et al.* 1992, McSween *et al.* 1992, McSween 1992). Shestopalov and Golubeva (1991, 1992) have found a correlation between the u-x color index and a spectral absorption band at 505 nm. They concluded that the differences between stony meteorites and S-type asteroids are caused by a systematic difference in their surface material composition.

Specific comparisons between individual asteroid and meteorite classes, based on spectral data, showed that a number of intriguing similarities indeed exist, involving both main-belt (Hiroi and Takeda 1990, Burbine *et al.* 1992) and near-Earth asteroids (Cruikshank *et al.* 1991a, Gaffey *et al.* 1992). Laboratory work on meteorite spectra has included exploring such specific problems as the effects of mixing different mineralogical types (Hiroi *et al.* 1993), and using powdered meteorite samples (Salisbury *et al.* 1991). Geologic processes on asteroids required to produce individual meteorite classes have been modeled in some detail (Kargel 1991, Warren and Kallemeyn 1992, Rubin and Mittlefehldt 1993, Benoit and Sears 1993).

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