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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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1. INTRODUCTION

This report has, following the usual practice in Commission 15, been compiled primarily by the chairpersons of the two working groups. E. Tedesco prepared the entire section about Asteroids and Meteorites. H. U. Keller prepared the section about Comets using material originally prepared by E. Kührt (nuclei), H. Böhnhardt (dust), R. Schulz (neutral gas), and W.-H. Ip (plasma). M. F. A'Hearn did minor editing to merge the two reports and fit the report into the allotted space.

Material was taken from both major areas regarding the relationship between comets and asteroids and combined into a single section. The only two objects with official IAU designations both as comets and as asteroids, 2060 Chiron and 4015 = 107P/Wilson-Harrington, are treated in this section, together with papers about the evolution of comets into asteroids. With the introduction during this triennium of a new system for designating comets, the reader will find a mixture of new and old designations (which are still officially acceptable for comets previously designated), generally the designation that one of the authors thought the reader would find most familiar. Both asteroids and comets are referred to by a designation and a name at the first appearance but often by name only when there is no confusion at susequent appearances.

Due to the explosion of literature in the field, this report deviates from past practice and does not include a comprehensive bibliography. A comprehensive bibliography would have taken by itself more than half the allotted pages. We have therefore prepared a selective review of results, citing of order half the actual papers published, but giving no list of references. References are cited in the text by year, and in the case of the asteroidal references also with a sequential number indicating the number of the reference in the database of references about asteroids. Thus (1994, 17) refers to the 17th paper in the database of asteroidal references for this triennium and that paper was published in 1994. Since there are still fewer than 1993 papers published per triennium, there should be no confusion. It is the intention of the commission to make the comprehensive list of references available *via the* commission's home page which will be established on the World Wide Web as a link from the IAU's home page.

2. ASTEROIDS AND METEORITES

In this section, papers related to asteroid physical studies and their connections with meteorites will be briefly summarized. The treatment of meteorites will be limited to those aspects directly related to the physical studies of asteroids. The relationship to comets is treated separately in a transition section. This report covers the period July 1993 through June 1996, inclusive. A search of the literature for this period found more than 400 papers directly related to the study of asteroids. This is more than double the number of papers referenced in the previous report.

A portion of IAU Symposium 160 (a.k.a. "ASTEROIDS, COMETS, METEORS 1993"), which met in Belgirate, Italy 1993 June 14-18, was devoted to asteroids. The proceedings of this meeting (edited by A. Milani, M. Di Martino, and A. Cellino and published by Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994) are referred to in this report; readers should refer to the source for the details and to the complete review by Vilas (1995).

I. Appenzeller (ed.), Reports on Astronomy, Vol. XXIIIA, 183–202.

Likewise, papers from four "hazard" workshops held between April 1991 and May 1993 were collected, updated, and published as the 24th book in the Space Science Series (Gehrels 1994). Again, readers are referred directly to this 1,300 page book for details and to the review by R. Wilson (1995). Additional discussions on this topic include those by Binzel (1995), Chapman and Morisson (1994), Hardy (1993), Hill (1995), Nadis (1995), and Sagan (1994). See the subsection on NEOs below for additional publications related to this topic.

Following the format adopted by Zappalà and Farinella in the previous transactions, the material will be organized under a series of arbitrary categories (the numbers in parentheses are the number of articles assigned to that category): 1. Asteroid sizes, size distribution, and masses (7); 2. Photometry, shapes, disk-resolved images, rotations, and pole orientations (50); 3. Radar, millimeter, radiometry, polarimetry, interferometry, and occultations (18); 4. Binaries and families (14); 5. Spectra, taxonomy, and compositions (32); 6. Origin, impact studies, and collisional evolution (31); 7. Asteroids which have been (or are planned to be) visited by spacecraft (24); 8. The Asteroid - Meteor - Meteorite Interface (81); 9. Near-Earth Objects (NEOs), including papers on their "Hazard" aspects (62); 10. Trojans of Mars and Jupiter (8); and 11. Miscellaneous (78). In many cases a given paper could have been assigned to one of several different categories. The category to which it was ultimately assigned was at the whim of the report writer. Also, the accuracy and completeness of the publications database is far from perfect.

2.1. ASTEROID SIZES, SIZE DISTRIBUTION, AND MASSES

Sitarski and Todororovicjuchniewicz (1995, 350) published mass determinations for 1 Ceres and 4 Vesta based upon their perturbations on four asteroids. Muinonen, Bowell, and Lumme (1995, 277) investigated the relationships among asteroid size, albedo, and magnitude distributions. Hughes and colleagues (1994, 168, 1995, 169, and 1994, 170) discussed the historical unraveling of the diameters of the first four asteroids, the asteroidal sphericity limit, and the asteroid size distribution and its significance.

2.2. PHOTOMETRY, SHAPES, DISK-RESOLVED IMAGES, ROTATIONS, AND POLE ORIENTATIONS

Lightcurve photometry continues to be the most active area of observational asteroid astronomy. New lightcurve observations were published for 204 different asteroids in 30 papers and theoretical and/or model results in 13 papers. For example: Barucci, Di Martino, and colleagues continued their lightcurve survey of small (diameter < 50 km) asteroids (1994, 19, 97, and 1996, 10). Such studies provide the observational material upon which investigations of the evolution of asteroidal spin rates (Fulchignoni *et al.*, 1995, 116) and the existence of asteroidal "rubble piles" (Harris, 1996, 142) are based.

McCarthy, Freeman, and Drummond (1994, 235) published high-resolution, rotationally resolved images of Vesta obtained at 1.65 μm and Stern *et al.* (1995, 359) obtained disk-resolved images of 1 Ceres (and Pluto) with the Hubble Space Telescope.

2.3. STUDIES USING RADAR, MILLIMETER, RADIOMETRY, POLARIMETRY, INTERFEROMETRY, OR OCCULTATION TECHNIQUES

Altenhoff *et al.* (1994, 7) used bolometric observations at 250 GHz of fifteen minor planets to show that the emissivity of these objects is close to unity. This results in an independent method to determine the absolute calibration scale of radio observations at mm wavelengths.

Andre *et al.* (1994, 8) describe a speckle imaging program begun at the 2-m Bernard Lyot telescope at the Pic du Midi Observatory, a site renowned for the exceptional quality of its skies during a significant part of the year. They expect to obtain a resolution of 0.06" in V using a speckle camera they have built and using the image restoration methods, based on bispectral phase recovery with least-squares minimization followed by regularized deconvolution, which they have developed.

Broglia, Manara, and Farinella (1994, 54) and Broglia and Manara (1994, 53) report on rotationally-resolved polarimetric observations of 6 Hebe and 51 Nemausa. For Nemausa they found a rotational modulation of polarization with a period equal to one third the rotational period which they interpret as suggesting a complex variegation over the asteroid's surface. For Hebe they report a 0.17% variation of the degree of linear polarization over a rotational cycle, together with a small variation of the position angle of the polarization plane with a frequency of twice the rotation rate. They interpret these results to indicate that Hebe's surface is optically heterogeneous, probably as a consequence of albedo and/or

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texture changes. They note that rotationally resolved spectroscopic observations are needed to assess whether the surface is also compositionally heterogeneous. They claim that, if found, this would rule it out as a possible source of undifferentiated meteorites, such as the ordinary chondrites.

Lupishko *et al.* (1995, 220) present UBVRI polarimetric observations of the near-Earth asteroid 4179 Toutatis carried out at the Crimean Astrophysical Observatory over six nights in December 1992-January 1993 and covering phase angles in the range 15.8 deg – 51.4 deg. Spectral dependencies of the positive polarization, polarimetric slope, and inversion angle were observed for the first time. The degree of the linear positive polarization decreases with increasing wavelength, supporting the inversion effect of the polarization spectral dependence of S-type asteroids. Their data show a fact unknown for asteroids before - the presence of polarization unconnected with the scattering plane. Mukai *et al.* (1994,280) published polarimetric observations of 4179 Toutatis at four wavelengths during 23 nights in December 1992 and January 1993. They found no peak in the linear polarization between phase angles of 0.3° and 101.3°. The inversion angle of about 20° and the polarimetric slope near the inversion angle of about 0.1%/° is consistent with Toutatis being an S-class asteroid. Model calculations of the phase angle dependence of polarization suggest that Toutatis is covered by a coarse regolith on its inhomogeneous rough surfaces.

Shkuratov (1994, 344) reviews experimental and theoretical studies of the backscattering phenomenon as it relates to the production of negative polarization. Shkuratov demonstrates that negative polarization is a characteristic of all atmosphereless celestial bodies and that the most pronounced negative polarization is observed for low albedo bodies such as C-class asteroids, carbonaceous chondrites, and mixtures of different-albedo materials of very fine structure. He notes that the opposition effect and negative polarization are often observed together, that in samples made to imitate planetary regoliths those with similar particle size distributions but different albedos reveal a horseshoe-shaped dependence of the minimum polarization as a function of albedo, and that dielectric substances exhibit deep negative polarization branches only when their surfaces have a particle size distribution with a characteristic size close to that of the observation wavelength.

Shkuratov *et al.* (1994, 345) examine about a dozen physical mechanisms and models which attempt to explain the negative polarization of light scattered by atmosphereless celestial bodies. They conclude that the so-called interference or coherent backscattering mechanism is the most promising model primarily because models based on that mechanism use well-defined physical parameters to explain both negative polarization and the opposition effect and are supported by laboratory experiments, particularly those showing enhancement of negative polarization with decreasing particle size down to the wavelength of light. According to this model, pronounced negative branches of polarization, like those of C-class asteroids, may indicate a high degree of optical inhomogeneity of light-scattering surfaces at small scales.

Goidet-Devel, Renard, and Levasseur-Regourd (1995, 131) published synthetic polarization-phase curves and derived characteristic polarimetric parameters for different classes of asteroids. Lupishko and Mohamed (1996, 221) published a new polarimetric albedo scale based upon recent IRAS and ground-based radiometric albedos and those obtained from stellar occultations.

A list of 155 predicted occultations of stars by asteroids in 1995 and 1996 was published by Wasserman, Millis, and Bowell (1995, 386).

Six papers reporting or discussing radar observations were published. Nelson and Nolan (1995, 286) discuss what can be learned from radar images of asteroids. Andrews, Hudson, and Psaltis (1995, 9) published the results of their laboratory optical and radar imaging of scale models, while Hudson and Ostro (1994, 167) presented a model for the shape of 4769 Castalia from inversion of radar images. Zaytsev *et al.* (1993, 411) described their 6-cm radar observations of 4179 Toutatis and Stooke (1996, 364) presented a preliminary map of Toutatis based upon delay-Doppler radar observations. Stooke concluded that Toutatis may possess grooves like those of Phobos, Gaspra and Ida.

De Pater *et al.* (1994, 92) reported on Goldstone-VLA, radar aperture-synthesis observations of the mainbelt asteroids 324 Bamberga and 7 Iris and the near-Earth asteroids 1991 EE and 4179 Toutatis. From these observations they concluded that Bamberga's spin vector is within 40° of the south ecliptic pole, and that the twofold ambiguity in Iris's pole direction (P. Magnusson, 1989) is resolved in favor of the ecliptic coordinates $\lambda = 15°, \beta = +25°$. Their results are consistent with radiometric estimates of Bamberga's size and with the hypothesis that the asteroid is overlain by a regolith having a porosity of approximately 50%.

2.4. BINARIES AND FAMILIES

The remarkable discovery of Dactyl orbiting 243 Ida is discussed below in the section on studies from spacecraft. The frequency of binary systems in the main belt remains unknown, however, due to the limitations of the observational techniques available for searching for satellites there (Roberts *et al.*, 1995, 317). Prokofeva and Demchik (1994, 304) argue for the duplicity of the main-belt asteroid 87 Sylvia based upon Fourier analysis of simultaneous BVR lightcurves.

Arguing that radar and lightcurve data suggest that a significant fraction of near-Earth asteroids are contact, or nearly contact, binary systems, Farinella and Chauvineau (1993, 108) and Chauvineau and Farinella (1995, 74) examine the dynamical evolution of such systems. They found that binaries have the relative orbit of their components changed when they experience close encounters with the Earth, and other terrestrial planets. The end-product of this evolution is either the escape of the components or a collision between them. They suggest that this may explain the origin of contact or nearly-contact systems such as 4769 Castalia and 4179 Toutatis, of very slow rotators (tidally despun while members of a binary system), such as 887 Alinda, 3288 Seleucus and 3102 1981 QA, and of pairs of Earth-approaching asteroids with similar (rare) compositions, such as 3551 Verenia and 3908 1980 PA. Additionally, impacts by relatively young, well-separated binaries may explain the existence of doublet craters.

Significant activity has taken place concerning asteroid families, with no fewer than ten papers addressing this issue. Zappalà *et al.* (1994, 409), using a sample of 6,212 main belt asteroids, placed 2,114 into 20 high-reliability families. As many as 242 additional asteroids could be grouped into a further 29 families by relaxing the reliability requirements. This result confirms earlier findings that a significant fraction of main belt asteroids belong to families. They conclude that the main features of their family classification are stable and reliable enough to guide future physical studies of asteroids, but note that, as the database of osculating elements grows it is likely that important details on the structure of individual families will emerge and lead to the discovery of new families originating from smaller parent bodies.

In other papers on this subject Gorbanev and Kramer (1993, 132) discuss the structure and evolution of "asteroidal" meteor swarms; Bendjoya (1993, 27) compares 2-D and 3-D wavelet analysis methods for the determination of asteroid families; Cellino and Zappalà (1993, 67) discuss the origin and evolution of the new big families (called 'clans') in terms of: 1. a primordial single event followed by subsequent collisions of the fragments, 2. a super-catastrophic original impact, and 3. different collisional events overlapping by chance; Zaninetti, Cellino and Zappalà (1995,408) determined fractal dimensions of the size distribution for some of the most important asteroid families in order to provide information on the processes of fragmentation, since families are thought to be the outcomes of a number of collisional disruptions of asteroidal bodies; Migliorini *et al.* (1995,251) estimate the numbers of interlopers within asteroid families; and Milani and Farinella (1994, 260) estimate the age of the Veritas asteroid family.

Milani and Farinella (1995, 257) show that when asteroid 2953 Vysheslavia, a Koronis family member about 15 km in diameter which is located very close to the outer edge of the 5/2 Kirkwood gap, falls into that resonance, it will approach Jupiter and end up in a hyperbolic orbit. The typical dynamical lifetime is of the order of 10 Myr. This 'marginally unstable' region of the orbital element space bordering the 5/2 resonance is only 10^{-3} AU wide in semimajor axis. They conclude that Vysheslavia has stayed in its current 'dangerous' location in orbital element space for a time much shorter than the age of the Solar System and discuss several hypotheses on the origin of this object, including a comparatively recent collision in the Koronis family and the possible implantation into a quasi-stable main-belt orbit of a stray body on a cometary orbit. They note that physical observations are needed to discriminate among these possibilities.

Wasson *et al.* (1996, 389) present an argument for the formation of the Vesta dynamical family and the main asteroid dust band discovered by IRAS being due to an oblique impact on Vesta.

2.5. SPECTRA, TAXONOMY, AND COMPOSITIONS

Papers on asteroid taxonomic classification were published by Howell, Merenyi, and Lebofsky (1994, 163), Fulchignoni, Barucci, and Tedesco (1995, 117), and Birlan, Barucci, and Fulchignoni (1996, 41).

Howell *et al.* used data from the 52-color asteroid survey (Bell *et al.*, 1988) together with the 8-color asteroid survey (Zellner *et al.*, 1985) to create $0.3 - 2.5\mu m$ spectra. They then used an artificial neural network to cluster these asteroid spectra based on their similarity to each other. They also used the neural network in a supervised mode to associate the established clusters with taxonomic classes. Results

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of their classification agree with the principal component cluster-analysis classification based on the 8-color data alone. When extending the spectral range using the 52-color survey data, they find that some modification of the principal component classes is required to produce a cleaner, self-consistent set of taxonomic classes, after which the network correctly classifies both the training examples, and additional spectra into the correct class with an average accuracy of 90%. The neural network classification supports the separation of the K class from the S class, as suggested by Bell *et al.* (1987), based on the near-infrared spectrum. They define two end-member subclasses which seem to have compositional significance within the S class. The network clustering suggests some additional structure within the E-, M-, and P-class asteroids, even in the absence of albedo information, which is the only discriminant between these in the principal component, three-parameter, or G-mode classification systems.

Fulchignoni *et al.* used a common data set to compare the G-mode and three-parameter classification techniques and found that, at a 94% confidence level, the two methods yield the same classifications. Birlan *et al.* used a revised version of the G-mode multivariate statistics to analyze a sample of 84 asteroids. This sample of asteroids is described by 29 variables, namely 23 colors between 0.9 and 2.35μm obtained from the data base collected by Bell *et al.* (private communication), 5 colors between 0.3 and 0.85μm from the ECAS survey (Zellner *et al.* 1985), and the revised IRAS albedo (Tedesco *et al.* 1992). They note the role of the IR colors in separating the various groups, particularly with regard to the fine subdivisions within the S and C taxonomic classes.

Vilas (1994, 380 and 381; 1995, 382) discusses efficient observational methods for detecting water of hydration on small solar system bodies.

Vilas, Jarvis, and Gaffey (1994, 383) report the identification of absorption features near 0.625 and 0.85 μm in the spectra of five low-albedo main-belt and outer-belt asteroids. They attribute these absorption features to charge transfer transitions in minerals such as goethite, hematite, and jarosite that are products of the aqueous alteration of anhydrous silicates. A shoulder near 0.63 μm has also been identified in the absorption feature centered near 0.7 μm attributed to oxidized iron in phyllosilicates found predominantly in the reflectance spectra of C- and G-class asteroids. They note that the coexistence of iron oxides with phyllosilicates in asteroids believed to have undergone aqueous alteration is expected based upon analogy with terrestrial aqueous alteration and the observed mineralogy of carbonaceous chondrites. However, the number of low-albedo asteroids having only iron alteration absorption features compared to the number of low-albedo asteroids having spectral characteristics indicative of phyllosilicates is small. Hence, they conclude that either the conditions under which these asteroids formed are rare, or the iron alteration minerals could be formed in the interiors of objects where phyllosilicates dominate the surface mineralogy.

Spectroscopic observations at visible and near-infrared wavelengths of low-albedo, outer-belt asteroids (primarily C-, P-, and D-class asteroids) were published by Barucci *et al.* (1994, 21), Dahlgren and Lagerkvist (1995, 88), Fitzsimmons *et al.* (1994, 111), Lagerkvist *et al.* (1993, 207 and 208), and Lazzarin, Barbieri, and Barucci (1995, 211). Low resolution spectra of Koronis family members, including 243 Ida, were published by Barucci and Lazzarin (1993, 20).

Xu *et al.* (1995, 402) presented the first results from their Small Main-belt Asteroid Spectroscopic Survey (SMASS), using 0.4-to-1-μm ccd-spectra of 316 asteroids. More than half the objects have diameters $<$ 20 km. They found that the majority of the small main-belt asteroids, like the large asteroids, belong to the S and C classes, but that two new classes are justified, which they call J and O. They note that small asteroids display more diversity in spectral absorption features than larger ones, which may indicate a greater variation of compositions in the small asteroid population. They found a few candidates for olivine-rich asteroids within the S class and, although the total number of olivine-rich candidates is relatively small, they present evidence suggesting that such objects are more prevalent at smaller sizes.

Luu, Jewitt, and Cloutis (1994, 224) obtained near-infrared spectra of a sample of primitive objects including 2 Centaurs (2060 Chiron and 5145 Pholus) and 16 P- and D-type asteroids. They found that Pholus exhibits broad adsorption features at 2.07 and 2.27 μm, as well as a weak feature at 1.72 μm . The 1.72- and 2.27-μm features are similar to those seen in a laboratory tar sand sample. No distinct absorption features are found in other objects, including Chiron, which displays a spectrally neutral continuum. A comparison of the P- and D-type asteroid spectra with laboratory measurements shows no compelling evidence for hydrocarbon overtones seen in terrestrial bituminous tar sands.

Cloutis, Gaffey, and Moslow (1994, 83) studied the 0.3-2.6-μm spectral reflectance of carbon polymorphs (graphite, carbon black, diamond), carbides (silicon carbide, cementite), and macromolecular organic-bearing materials (coal, coal tar extract, oil sand, oil shale) and found them to vary from sample to sample and among groups. The carbon polymorphs are readily distinguishable on the basis of their visible-near-infrared spectral slopes and shapes. The spectra of macromolecular organic-bearing materials show increases in reflectance toward longer wavelengths, exceeding the reflectance rise of more carbon-rich materials. Reflectance spectra of carbonaceous materials are affected by the crystal structure, composition, and degree of order/disorder of the samples. They noted that these characteristic spectral properties can potentially be exploited to identify individual carbonaceous grains in meteorites or to conduct remote sensing geothermometry and identification of carbonaceous phases on asteroids. Cloutis (1996, 82) notes that identification of organic molecules on candidate asteroid surfaces has been hampered by a number of factors, including low albedos, large heliocentric distances, and a general lack of detailed spectral-compositional information on candidate terrestrial organic materials. Preliminary analysis of some candidate asteroid spectra in light of the laboratory data suggests that asteroidal organics are heterogeneous in terms of abundance and composition. To date, identification of organics (*i.e.*, hydrocarbons) on asteroid surfaces has been restricted to two asteroids: 5145 Pholus and 130 Elektra. Other asteroids have been identified as possibly possessing other C-bearing molecules, but not necessarily hydrocarbons.

Wilson, Sagan, and Thompson (1994, 397) used Hapke scattering theory and optical constants measured in their laboratory to examine the ability of mixtures of a number of organic solids and ices to reproduce the observed spectrum and phase variation of 5145 Pholus. The primary materials considered were poly-HCN, kerogen, Murchison organic extract, Titan tholin, ice tholin, and water ice. In a computer grid search of over 10 million models, they found an excellent fit with 10-μm particles with an intraparticle mixture of 15% Titan tholin, 10% poly-HCN, and 75% water ice. They found that replacing water ice with ammonia ice improves the fits significantly, while using a pure hydrocarbon tholin (Tholin alpha) instead of Titan tholin makes only modest improvements. All acceptable fits require Titan tholin or some comparable material to provide the steep slope in the visible, and poly-HCN or some comparable material to provide strong absorption in the near-infrared. A pure Titan tholin surface with 16-μm particles, as well as all acceptable Pholus models, fit the present spectrophotometric data for the transplutonian object 1992 QB1.

Buemi *et al.* (1994, 58) present the results of experimental studies on the development of the -SiH stretching band by implantation of 1.5 keV protons into silicon, quartz, palagonite, and feldspar. They conclude that their results seem to argue against the possibility of observing asteroidal (or cometary) spectral features due to -SiH groups formed by implantation of solar wind protons in silicate surfaces. Proton implantation in silicon wafers produces in fact an observable -SiH stretching band while proton implantation in silicates fails in forming that band.

Hiroi *et al.* (1993, 157) compared the 0.3-to-2.6 μm reflectance spectra of 14 C, G, B, and F asteroids and 21 carbonaceous chondrite powders. They showed that only three thermally metamorphosed CM-CI chondrites with a weak UV absorption have close counterparts among those asteroids. They compared reflectance spectra of a heated Murchison CM2 chondrite with the average C and G class asteroid spectra and found that Murchison heated at 600 to 1000 C exhibits a similar weak UV absorption and provides the best analog for those spectra. Based upon a comparison of UV absorption strengths between 160 C, G, B, and F asteroids and carbonaceous chondrites they concluded that the surface minerals of most of those asteroids are thermally metamorphosed at temperatures around 600 to 1000 C.

Shestopalov and Golubeva (1993, 339) report the detection of Titanium in the surface regolith of asteroid 71 Niobe.

Britt *et al.* (1994, 52) note that whereas the E and M asteroid classes have very similar red-sloped featureless spectra in the visible and near-IR wavelengths, it is their differences in albedo that form the basis for distinguishing these classes. The M class (moderately high albedo) is generally thought to be composed of Fe-Ni metal, while the (high albedo) E class is generally thought to be dominated by enstatite. However, they note that over the past decade observational evidence (hydration features in the spectra) has been accumulating indicating that at least some of the M asteroids may not be metallic and some of the E asteroids may not be enstatite. They speculate that hydrous E and M asteroids may represent new classes of asteroids that have surface mineralogies unlike anything so far seen in the meteorite collections. Observations imply that the hydrated E and M asteroids have very little in common with the other anhydrous members of their taxonomic classes that are probably igneous (E and M asteroids) and metal-rich (M asteroids).

Hiroi, Vilas, and Sunshine (1996, 158) report the detection of minor absorption bands in the 0.55-to-0.7 μm wavelength range in reflectance spectra of S asteroids. These spectra have been compared with those of spinel-group minerals using the modified Gaussian model. They find that most of these S asteroids have two absorption bands around 0.6 and 0.67 μm. Of the spinel-group minerals examined in their study, the 0.6 and 0.67 μm bands are most consistent with those seen in chromite. These new findings suggest a possible common existence of spinel-group minerals in the solar system.

Roettger and Buratti (1994,319) present spectral reflectances, phase curves, and geometric albedos between 2300 and 3250 Å for 45 asteroids using data acquired by the International Ultraviolet Explorer satellite. With the exception of 44 Nysa (E-class, geometric albedo = 0.3 at 2950 Å), they found consistently low geometric albedos, ranging from 0.02 for C-class asteroids to 0.08 for M-class asteroids. They found that the three major asteroid taxonomic classes are distinguished primarily by their albedos in the UV, although the S class is generally redder than the C or M classes.

2.6. ORIGIN, IMPACT STUDIES, AND COLLISIONAL EVOLUTION

As noted in the previous transactions, collisions, in particular those which catastrophically shatter the target objects, represent the most important process currently causing the asteroid population to evolve.

Benz, Asphaug, and Ryan (1994, 31) give the results of numerical simulations of catastrophic disruption. Bottke *et al.* (1994, 48) note that the probability distribution for impact velocities between two given asteroids is wide, non-Gaussian, and often contains spikes. Campo Bagatin, Farinella, and Petit (1994, 65) applied the algorithm developed by Petit and Farinella (1993) to model the outcomes of impacts between asteroids of different sizes, to show that a crucial feature of these models is the assumed relationship between the velocity and mass of the fragments.

Chen, Ahrens, and Hide (1995, 75) note that the observed magnetism of asteroids such as Gaspra and Ida may have resulted from an impact-induced shock wave. The scaling law of Housen *et al.* (1991) for catastrophic asteroid impact disaggregation imposes a constraint on the degree to which small planetary bodies may be magnetized and yet survive fragmentation by the same event. Their modeling results show it is possible that Ida was magnetized when a large impact fractured a 125 ± 22-km-radius protoasteroid to form the Koronis family. Similarly, they calculate that Gaspra could be a magnetized fragment of a 45 ± 15-km-radius protoasteroid.

Davis, Ryan, and Farinella (1994, 89) note that a critical element for understanding asteroidal collisional evolution is the scaling law needed to link laboratory impact experiments to asteroidal bodies, ranging in size from meters to several hundreds of km. They report that recent work on scaling theories has produced algorithms for computing the specific energy, Q, required to fragment bodies of various sizes, based on two approaches: the strain-rate scaling theory of Housen and Holsapple based on dimensional analysis, and the 2-D hydrocode calculations of Ryan and Melosh (1994). The strain-rate scaling predicts a decrease of about an order of magnitude when going from laboratory sized bodies, 10 cm, to bodies a few tens of km in size, whereas for larger sizes Q grows due to gravitational self-compression. The hydrocode results show an even stronger dependence on size, with a Q decrease of 2-3 orders of magnitude between 10 cm and 25 km, depending on the properties of the material. These model calculations show that a comparatively large value of Q is needed to match the observed size distribution and to preserve Vesta's crust. Simple energy scaling with gravitational self-compression in agreement with the laboratory experiments of Housen *et al.* (1991) does the best job of reproducing the observed asteroid belt.

Results of laboratory experiments or modeling of fragmentation processes have been published by Giblin *et al.* (1994, 125), Love and Ahrens (1996, 219), Martelli *et al.* (1994, 229), Nakamura, Fujiwara, and Kadono (1994, 285), Nolan, Asphaug, and Greenberg (1993, 289), Paolicchi, Verlicchi, and Cellino (1993, 295), Ryan (1996, 326), Shirono *et al.* (1993, 342), and Verlicchi *et al.* (1994, 377).

Studies relating collisional process and meteorites include those by Benedix *et al.* (1996, 28), Flynn (1993, 112), Keil, Haack, and Scott (1994, 184), and Scott *et al.* (1994, 336). Those relating collisional process and asteroid families include Marzari, Davis, and Vanzani (1994, 285), Paolicchi (1994, 293 and 294), Petit and Farinella (1993, 297), and Rivkin and Bottke (1996, 316).

2.7. ASTEROIDS WHICH HAVE BEEN OR ARE PLANNED TO BE VISITED BY SPACECRAFT

Asteroid 243 Ida is the second asteroid to have been visited by a spacecraft, albeit not one designed for doing asteroid science. The Galileo spacecraft (Belton *et al.* 1994, 26) obtained high-resolution images

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and other detailed data during its flyby. Perhaps the most surprising finding of the Ida flyby was the discovery of a small satellite later named Dactyl. A flurry of papers followed this discovery (Chapman *et al.*, 1994, 70; Belton *et al.*, 1995, 25; Binzel, 1995, 36; Chapman, 1995, 69; Chapman *et al.*, 1995, 73; Giese *et al.*, 1996, 126; Zeitler, Oberst, and Giese, 1996, 412). According to Chapman *et al.*, 1994 Ida is a highly irregular body, about 56 km long, heavily covered with craters, and with many interesting geological features. Dactyl is approximately 1.5 km in diameter, has an albedo and spectral reflectance similar to that of Ida, and orbits Ida in a prograde direction with a period of roughly 20 hr. Belton *et al.* (1995, 25) report Ida's bulk density to be approximately 2.5 g/cm3.

The next asteroids scheduled to be visited by spacecraft will utilize spacecraft designed specifically for doing asteroid science. These include the proposed United States Department of Defense Clementine II and the NASA Near Earth Asteroid Rendezvous (NEAR) missions.

NEAR was launched on 17 February 1996 and will rendezvous with the Earth-crossing asteroid 433 Eros on 6 Feb 1999, and provide one year of orbital data coverage. Papers describing NEAR instrumentation have been published by Murchie *et al.*, (1996, 281), Robinson *et al.*, (1995, 318) and Trombka *et al.*, (1995, 373). En route to Eros NEAR is planned to fly by the 60 km diameter main belt asteroid 253 Mathilde. This is substantially larger than the diameters of either Gaspra (16 km) or Ida (33 km), which would make Mathilde the largest asteroid to be visited by a spacecraft. In addition, the proposed NEAR encounter with Mathilde will provide the first close-up images of a C-class asteroid. Preliminary plans call for a closest approach distance of 1,200 km on June 27, 1997. Ground-based observations of 253 Mathilde in expectation of the NEAR encounter have already begun (Binzel, Burbine, and Bus, 1996, 38). The NEAR mission's World Wide Web site home page is at http://hurlbut.jhuapl.edu/NEAR/

Clementine II is a United States Department of Defense spacecraft which is planned to fly by several Near Earth Asteroids (Weisman, 1995, 391). It will fire projectiles into its target asteroids and observe the results, including the debris clouds created by these impacts.

2.8. THE ASTEROID - METEOR - METEORITE INTERFACE

Significant progress continues to be made in one of the most important issues in planetary science: the relationship between asteroids and meteorites and the identification of meteorite parent bodies. Chapman (1995, 69), using the Galileo observations of Gaspra, Ida, and Dactyl as well as other recent asteroid research, suggests that meteorites (and their larger siblings, the Earth-approaching asteroids) are derived, in a fairly representative fashion, from main-belt asteroids, which include all common meteorite types, including ordinary chondrites. The immediate (and intermediate) parent bodies are highly fractured, often with compound, rubble-pile-like structures, that represent a long history of cascading fragmentation. He goes on to note that is doubtful how much these modern parent bodies resemble the original bodies that condensed and accreted in the inner solar system.

Because this subject area contains, by a wide margin, the most publications, the subject area has been further sub-divided into subsections, within each of which the major papers are noted and representative highlights from some are presented.

2.8.1. *Vesta as the probable ultimate HED (howardite, eucrite, and diogenite) parent body*

Asphaug (1994, 14), Bell (1993, 23), Eugster and Michel (1993, 104 and 105), Metzlet *et al.* (1995, 246), Miyamoto and Takeda (1994, 263), Wilson and Keil (1995, 395; 1996, 396), and Yamaguchi, Taylor and Keil (1995, 403) discuss metamorphism, excavation, and/or delivery mechanisms for the HED meteorites. Hiroi, Pieters, and Takeda (1994, 156) estimate the grain size of the surface regolith of Vesta by comparing its reflectance spectra (0.3-2.6 μm) with those of HED meteorites.

2.8.2. *Connections between asteroids and meteor streams*

Asher, Clube, and Steel (1993, 13), Klacka (1995, 191), and Ziolkowski (1995, 414) discuss asteroids with orbits similar to the Taurid complex and conclude that both probably have a common origin. Williams and Wu (1993, 394) discuss the relationship between the Geminid Meteor Stream and 3200 Phaethon, while Steel (1995, 357) investigates associations between earth-crossing asteroids and meteor streams.

Benoit and Sears (1995, 29 and 30) used measurements of natural thermoluminescence on modern falls of chondrites to constrain the perihelion distance for individual meteorites and hence individual meteoroid bodies. They found that most meteorite bodies had perihelia of approximately 1 AU, with only a small fraction ($\sim$ 15%) having orbits with perihelia $<$ 0.85 AU and that there were no strong differences in the thermoluminescence distributions of H, L, and LL chondrites. One of their findings is that while the afternoon H chondrite falls show a broad spread of natural thermoluminescence levels (corresponding to $0.85 < q < 1.2$ AU), the morning falls show a very tight cluster, with a mean thermoluminescence corresponding to $q \sim 0.95$ AU. They note that one possible interpretation of these data is that, while the afternoon meteorites come from a number of different sources reflecting different degrees of orbital evolution, most of the morning H chondrites are derived from an Earth-crossing asteroid(s).

They also determined the "average" perihelion of ordinary chondrites over periods $< 10^3 - 10^5$ years prior to Earth impact. Their data suggest that the Lost City meteorite had $q \sim 1.0$ AU for at least the last 10^5 years while Innisfree had a perihelion as low as 0.8 AU within the last 10^5 years. They state that their data do not support a direct link between Farmington (thermoluminescent $q = 0.82$ AU) and the Taurid meteoroid complex ($q \sim 0.4$ AU). They observe a tendency for meteorites with large cosmic ray exposure ages (> 35 Ma) to have shallower perihelia, typically close to 0.8 AU, than those with relatively short cosmic ray exposure ages, which tend to have perihelia between 0.85 - 1.0 AU.

Hasegawa (1996, 145) discusses possible associations between daytime fireballs and asteroids while Jopke *et al.* (1995, 182) discuss the long-term dynamical evolution of 17 bright bolides, including four associated with meteorite finds. Jopke *et al.*'s results show dynamical mechanisms and evolutionary patterns similar to those recently found for near-Earth asteroids. They conclude that this suggests that the sources for km-sized near-Earth asteroids and meter-sized meteoroids are probably the same, and that the two types of bodies just sample different parts of the size distribution of a population of interplanetary objects with common dynamical features. They note that the results of their integrations are consistent with the idea that ordinary chondrites come from the inner part of the main asteroid belt.

Morbidelli *et al.* (1995, 270) discuss the delivery of meteorites through the ν_6 resonance. They conclude that asteroids near this resonance, in particular the largest ones, like 6 Hebe, 304 Olga, 739 Mandeville and 759 Vinifera, are probably efficient deliverers of meteorites and that the time required for these fragments to be transported into Earth-crossing orbits is typically on the order of 10^6 yr when the eccentricity is directly pumped up by the resonance, to $e \sim 0.6$, but longer when Mars encounters are needed as an intermediate process. Other asteroids inject a substantial fraction of their fragments into the 3/1 (623 Chimaera, 1892 Lucienne) and 5/2 (631 Philippina, 907 Rhoda, 1222 Tina) Kirkwood gaps. They note that all these asteroids should be the targets of detailed spectrophotometric investigations, to assess their similarity to some of the known meteorite types.

2.8.3. *Meteors and Meteoroids*

Meteors are the subject matter of Commission 22 but the papers mentioned here are particularly relevant to physical studies of asteroids. For example, Chyba, Thomas, and Zahnle (1993, 79) discuss the 1908 Tunguska explosion in terms of the atmospheric disruption of a stony asteroid.

Ceplecha (1994, 68) uses statistical data on meteoroids with sizes smaller than one meter to predict the flux of meteoroids impacting the Earth in the 1 to 10 meter size range. He presents a table of all 14 precisely-recorded fireballs belonging to meteoroids larger than 1 meter. He concludes that the majority of 10-meter size bodies are of cometary origin corresponding to the weakest known structure.

McCord *et al.* (1995, 236) report the results of an analysis of a meteoroid which entered Earth's atmosphere over the central Pacific Ocean on 1 February 1994. This entry was detected by infrared and visible wavelength sensors on board platforms operated by the U.S. Department of Defense. The object broke up into several fragments and created debris clouds which were tracked for over an hour. They determined the entry velocity to be about 24 km/s at an angle of approximately 45° on a heading of approximately 300°. From this, the object's heliocentric orbit just prior to entry was calculated to have $a \sim 1.6$ AU, $e \sim 0.65$, and $i = 2.1°$. They estimate the total kinetic energy of the meteoroid to be equivalent to 34 to 630 kilotons of TNT. From the kinetic energy and assuming that the object was composed of silicates with a density of 3.5 g/cm^3, they derived a mass range of 5×10^5 to 9×10^6 kg and a diameter between 6 and 17 meters.

Nemtchinov *et al.* (1995, 288) present an assessment of meteoroid characteristics using light curves obtained by satellite and ground-based networks. They note that a relatively small number of satellites in high altitude orbits provide coverage of most of the Earth's surface and that space-based infrared sensors have detected over 200 bright flashes in the atmosphere since 1972. The average number of detections per year is 30. In addition, they note that optical sensors have detected 16 light curves in the visible (mainly during the last year). They conclude that these bright flashes have been caused by the explosive disintegration of large meteoroids in the atmosphere. Their analysis provides important information on the frequency distribution of energy of the impacting meteoroids, including their sizes, strengths, and indications of their compositions. They report that the pre-atmospheric kinetic energies of the meteoroids which caused events observed on 15 April 1988, 1 October 1990, 4 October 1991, and 1 February 1994 were 8 - 9, 5 - 8, 1 - 2, and 40 kt TNT, respectively. Three were stones or chondrites and deposited their energy at altitudes of 30 to 45 km. The last was probably an iron and penetrated to an altitude of about 20 km. They point out that a 15 June 1994 event, also detected by satellites, is of special interest, as the meteoroid crossed the United States and ended as a meteorite fall near Montreal, Canada.

Melosh (1995, 243) discusses cratering dynamics and the delivery of meteorites from the surfaces of the Moon, Mars, and potentially other major planets or moons in the solar system. He concludes that ejection of lightly shocked rock debris from the surface of a planet into interplanetary space no longer seems as difficult as it once did. He notes that this process is currently supported by the discovery of meteorites from the moon and Mars, theoretical studies of the spall mechanism and perhaps hints of vapor plume acceleration, and experimental observations of fast, lightly shocked ejecta from rock targets.

2.8.4. *The Asteroid-Meteorite Connection*

Papers discussing the path linking telescopic measurements of asteroids with laboratory measurements of meteorites were published by Binzel (1995, 33), Burbine and Binzel (1995, 60), Delany (1993, 93), Eugster and Weigel (1995, 106), Haack *et al.*, (1996, 135), and Wasson (1995, 388). The origin of chondrites on S asteroids continues to be a lively area of investigation but the jury is still out, as exemplified by the results (a draw) of a debate between J. Bell and C. Chapman at the 1995 meeting of the Division for Planetary Sciences meeting, each supporting one of the two opposing hypotheses. Papers addressing this issue include those by Binzel (1996, 37), Binzel *et al.*, (1993, 34), Binzel *et al.*, (1993, 40), Britt (1996, 50), Consolmagno and Britt (1995, 85), Flynn (1996, 113), Gaffey (1995, 119; 1996, 120), Hutchison (1993, 171), Muenow, Keil, and McCoy (1995, 276), and Rubin (1994, 320).

2.8.5. *Spectroscopy*

While strictly speaking not directly related to physical observations of asteroids, laboratory spectroscopy of meteorite dust grains connects such observations with material from actual asteroids. In addition to those papers listed in the preceding two sections there were four others, given here, which are of interest to members of Commission 15: Calvin and King (1993, 63) present reflectance spectra of iron-bearing phyllosilicates and discuss their relationship to CM chondrites. Cloutis and Gaffey (1993, 84) use reflectance spectra of meteoritic metal, meteoritic troilite and the CR carbonaceous chondrite EET87770 to investigate the causes of the spectral differences between the surface of the E-class asteroid 44 Nysa and the opaque-free fraction of the Happy Canyon aubrite meteorite. Pieters and McFadden (1994, 299) discuss meteorite and asteroid reflectance spectroscopy in the context of providing clues to processes which occurred during early solar system history and Sanford (1993, 330) presents mid-infrared ($2.5 - 22.2\mu$m) transmission spectra of seven Antarctic ureilites and ten Antarctic H-5 ordinary chondrites.

2.8.6. *Metallic Asteroids-Meteorites*

Haack and Scott (1993, 134) present and discuss evidence for chemical fractionation in group IIIAB iron meteorites by dendritic crystallization of an asteroidal core. Herpfer and Larimer (1994, 148) and Larimer (1995, 210) discuss experimental studies into the formation of metallic cores in asteroids. The origin of the iron meteorite groups is discussed by Marti, Lavielle, and Jeannot (1995, 231). Revelle and Ceplecha (1994, 312) used two different techniques to analyze the U. S. Prairie Network fireballs in order to search for possible nickel-iron meteoroids. They discuss the possible relation between these fireballs and near-Earth M-class asteroids. Taylor (1993, 367) discusses the processes which produced differentiated meteorites inside asteroids.

2.8.7. *Chondrite Asteroid Parent Bodies*

The B-, C-, F-, and G-class asteroids are thought to be the likely parent bodies for the chondritic meteorites. Hiroi *et al.*, (1995, 153) present evidence for thermal metamorphism on some asteroids of these classes, while Hiroi *et al.*, (1996, 154) report detection of thermal metamorphism for two more CI/CM meteorites. Huang *et al.*, (1994, 166) discuss mechanisms for the formation of chondrites in a thick dynamic regolith. Krot, Scott, and Zolensky (1995, 199) present evidence for alteration and dehydration processes in the Allende parent asteroid. Rubin and Wasson (1995, 321) report variations of chondrite properties with the heliocentric distance at which they formed. Rubin (1995, 322) provides petrologic evidence for the collisional heating of chondritic asteroids. Scott, Krot, and Zolensky (1995, 337) review mineralogical variations among CV3 chondrites and conclude that the evidence suggests that all components, chondrules, matrices, and CAIs, were affected by various degrees of secondary mineralization. Zolensky (1995, 414) discusses cyclical regolith processes on hydrous asteroids.

2.8.8. *Asteroid Thermal Evolution*

In addition to the papers by Hiroi *et al.* noted previously, McSween and Grimm (1994,242) discuss ^{26}Al as an asteroidal heat source. Ghosh, McSween, and Baker (1995,123) attempted thermal modeling of asteroids using the finite element method. Ghosh and McSween (1996,124) present the results of a 100 Ma long thermal model for the 550-km diameter asteroid 4 Vesta based upon radionuclide and collisional heating. Pellas and Rasmussen (1994, 296) present a model for the thermal evolution of the Acapulcoite-Lodranite parent body.

2.8.9. *Space Weathering*

Space weathering is treated by Pieters *et al.* (1993, 298) and Gaffey (1996, 120). Pieters *et al.* discuss the issues raised by new lunar soil analyses and conclude that the Galileo multispectral images of Gaspra are highly suggestive of space weathering, similar to that occurring on the Moon but different in magnitude. Gaffey's discussion is based upon a detailed spectral analysis of the large S-class asteroid 6 Hebe. He believes that, while no large main-belt asteroid has yet been confirmed as an ordinary chondrite parent, Hebe is the best current possibility. Gaffey concludes that while the presence of a space weathering process on Ida and Gaspra appears well established, there still remains considerable uncertainty concerning its nature and ability to spectrally modify ordinary chondrites to match the slope and band depths of S-class asteroids.

2.9. NEAR-EARTH OBJECTS (NEOS), INCLUDING THE "HAZARD" ISSUE

In addition to the book on the hazards due to asteroidal impacts in the introductory paragraphs, more than 60 papers were published on various aspects of Near-Earth Objects, making this the second most active research area behind the asteroid-meteor-meteorite interface area.

Papers relating to the current impact probability (including orbital evolution and sources), impact mechanisms and effects, or mitigation schemes include those by Afonso, Gomes, and Florczak (1995, 2), A'Hearn (1995, 3), Babadzhanov, Zausaev, and Pushkaryov (1996, 24), Brunini, A. (1994, 57), Bykov (1995,62), Clarke (1993, 81), Covey *et al.* (1994, 86), Farinella *et al.* (1994, 109), Gehrels (1996, 122), Jach *et al.* (1994, 175), Harris and Hughes (1994, 143), Hecht (1995, 147), Hills and Leonard (1995, 151), Isobe and Yoshikawa (1996, 173), Ivashkin and Smirnov (1995, 174), Jobe (1993, 181), McGhee (1994, 240), Menichella, Paolicchi, and Farinella (1996, 245), Michel and Thomas (1996, 249), Miura, Takayama, and Iancu (1993, 262), Nadis (1995, 284), Pope *et al.* (1994,301), Rabinowitz (1994, 307), Rabinowitz and Wetherill (1995, 306), Rabinowitz *et al.* (1993, 308), Sagan and Ostro (1994, 327), Schmidt and Wasson (1993, 333), Solem (1993, 352), Stage and Rasmussen (1993, 355), Steel (1995, 358), Van den Bergh (1994, 374), and Vickery and Melosh (1993, 379).

Search efforts, strategies, and plans are discussed by Jackson *et al.* (1994, 177), Jedicke (1995, 179, 1996, 178), Monet (1995, 268), Reichhardt (1994, 311), Steel (1995, 356), and Tatum, Balam, and Aikman (1994, 366).

Physical studies of near-Earth asteroids were published by Belskaya, Lupishko, and Dovgopol (1996, 24), Hoffmann *et al.* (1993, 160), Howell *et al.* (1993, 161, 1994, 162), Kargel (1994, 183), Pravec *et al.* (1995, 302), and Prokofeva *et al.* (1995, 305).

Bottke and Melosh (1996, 46) note that a recent survey of Mars' northern plains by Ingrham *et al.* found a surprising paucity of doublet craters compared with the fraction of doublets found on Earth and Venus (a few % it vs. $\sim$ 10%). They state that previous results have shown that doublet craters are formed from two well-separated asteroids impacting at nearly the same time, such that two distinct craters are formed. They argue that these asteroids must be separated well in advance of planetary impact, which implies that a small but substantial number of asteroids must have satellites. Using a numerical model, they found that loosely bound asteroids ("rubble piles") encountering Earth or Venus may be pulled apart into large fragments by planetary tidal forces, which under certain circumstances may remain gravitationally bound to one another. They also found that many of these co-orbiting binary asteroids impact Earth or Venus while well-separated, and that they can reproduce the fraction of doublet craters found on Earth and Venus. By modifying this model they show that, although Mars' lower density does not prevent loosely bound asteroids from being pulled apart into large fragments, only a small fraction of these binaries become well-separated. Their model predicts that fewer than 3% of the asteroids impacting Mars produce doublet craters, in agreement with the observations.

Wichman and Wood (1995, 393) investigated linear crater chains on Ganymede and Callisto which they assume to provide an impact record of tidally disrupted bodies, like D/Shoemaker-Levy 9. They propose that the Davy crater chain on Earth's Moon records a similar tidal disruption event. They argue that the Davy chain differs from most lunar crater chains, which result from either volcanism or secondary impacts, but is similar in appearance to the crater chains observed on the Jovian satellites. They note that their tidal disruption models indicate that the much smaller size of the Davy chain is consistent with Earth's lower mass. Their models also indicate that most Earth-crossing comets and asteroids are moving too fast for fragment dispersion before impact to produce the observed crater chain length and conclude from this that the Davy chain and the Jovian satellite chains apparently result from bodies with different orbital characteristics. Furthermore, they argue that the limited dispersion of high velocity fragments at the Moon suggests that crater chains may not form for all disruption events or on all planetary satellites. They suggest that, based on modeled fragment dispersions elsewhere in the solar system, similar crater chains may be present on Iapetus, Titan, Titania, or Oberon.

2.10. TROJANS OF MARS AND JUPITER

The discovery of a Mars Trojan asteroid toward the end of the preceding triennium rekindled interest in the three-body problem. Mikkola *et al.* (1994, 252) analyzed the orbital evolution of the one known Mars Trojan (5261 Eureka) during the next 2 Myr. They concluded that strong perturbations by planets other than Mars seem to stabilize the eccentricity of the asteroid by stirring the high order resonances present in the elliptic restricted problem. As a result, the orbit appears stable at least on million-year time scales.

Mikkola and Innanen (1994, 253) performed numerical integrations for several dozen Mars Trojan test particles in a self-consistent model of the solar system. The integration period exceeded 4 Myr. They concentrated primarily on the dependence of the stability of the motion on the particles' orbital inclination and investigated the possibility of a chaotic component in the trajectories. They conclude that long-term stability for the particles appears possible only in two well-defined "inclination windows" ($15° \leq i \leq 30°$ and $32° \leq i \leq 44°$ with respect to Jupiter's orbit). They found, and tentatively identified, the decisive perturbing and destabilizing influences on the orbits, which seem to be simple secular resonances caused by Jupiter and/or Mars. Furthermore, they found that the variational equation solutions do not indicate chaoticity before the actual destabilization occurs, so that the instability is a threshold phenomenon rather than due to sensitive dependence on initial conditions.

Elst (1996, 103) discusses the discovery and rediscovery of Trojan asteroids. Muinonen and Bowell (1993, 279) used Bayesian *a priori* and *a posteriori* probability densities to determine asteroid orbital elements from optical astrometric observations. They note that for near-Earth asteroids and Jupiter Trojans, the two-body approximation can yield grossly erroneous uncertainty estimates because of the scattering effect of close planetary encounters or prolonged weak planetary perturbations.

Milani (1993, 256) computed proper elements for 174 asteroids (*i.e.*, for all available reliable orbits) in the 1:1 resonance with Jupiter.

Marzari, Scholl, and Farinella (1996, 234) computed collision rates and mutual impact velocities among Jupiter's Trojan asteroids while Marzari, Farinella, and Vanzani (1995, 233) investigated whether Trojan collisional families are a source for short-period comets. The latter used a collisional model based on the results of high-velocity laboratory impact experiments, and previously applied to main-belt asteroid families, to show that typical family-forming Trojan collisions eject a significant percentage (> 20%) of the resulting fragments into unstable orbits. Numerical integrations of these unstable orbits show that they soon experience close encounters with Jupiter and become indistinguishable from those of Jupiter-family comets (some of which are currently close to the 1:1 Jovian resonance), of comets undergoing temporary satellite captures by Jupiter (such as D/Shoemaker-Levy 9), and of objects with Jupiter-crossing or -approaching orbits (such as 944 Hidalgo, 2060 Chiron, 5145 Pholus, and 3552 Don Quixote). They conclude that reliable assessment of the efficiency and the time dependence of the transfer process is difficult, owing in particular to the poorly known size distribution of Trojans. However, they note that an order-of-magnitude estimate suggests that, if the fragment flux from the Trojan clouds over the last $\sim 10^6$ years has been close to the average over the solar system's lifetime, then a few tens of the 160 known short-period comets might have been generated by the catastrophic disruption of Jupiter Trojans.

2.11. MISCELLANEOUS

There were 78 papers which were not easiy classified into one of the previous categories. These include editorials and popular articles as well as some typical research ariticles. No sample can be representative, but in view of the recently reported finding of evidence for fossil life on Mars, the paper: "The Delivery of Organic-Matter from Asteroids and Comets to the Early Surface of Mars" by Flynn (1996, 114) is especially timely.

3. THE ASTEROID-COMET INTERFACE

This section contains papers which discuss the issue of objects which formed as comets but which have since undergone orbital and physical changes such that today they are virtually indistinguishable from asteroids. It also includes papers on either of the two objects which have dual classifications.

The aging of comets (Whipple, 1996) can cause an asteroid-like behavior as discussed by McFadden (1994). Jewitt (1996) discussed the essential differences between comets and asteroids and pointed out that the observation of activity is not a sufficient criterion to distinguish between these two classes of small bodies. Luu (1994, 222) also reviewed the comet to asteroid transition in general terms while McFadden *et al.* (1993, 239) discuss one such candidate transition object: "asteroid" 2201 Oljato.

Brownlee *et al.* (1993, 56) describe the properties of cometary and asteroidal interplanetary dust particles. Kulikova and Myshev (1995, 201) present models and results of stochastic modeling of ejection from comets and asteroids.

Solc, Stork, and Kozel (1994, 351), noting that impacts can bring geologically evolved asteroidal particles into cometary nuclei that consist of more primitive material, estimate the amount of such material captured by the nuclei of typical short-period comets.

Campins *et al.* (1995, 64) determined a radiometric diameter for the comet-asteroid transition object 4015 = 107P/Wilson-Harrington.

Chiron, a potential KBO has been extensively studied. Activity was found at a heliocentric distance of 13 AU (Luu, 1993a). CO seems to be the main molecule driving activity. Prialnik et al. (1995) proposed the crystallization of amorphous water ice as the source of such distant activity. Campins et al. (1994) deduced from infrared observations, when Chiron was near perihelion, that the nucleus is unexpectedly warm (130 K) indicating a fluffy structure. Altenhoff and Stumpff (1995, 1) determined a size for 2060 Chiron, from measurements at 250 GHz, about half that of previously published upper limits from observations at other wavelengths. The continuous outburst history and the dust coma presence around Chiron from 1989 to 1992 is addressed in a photometric monitoring program by (Luu, 1993).

4. COMETS

4.1. INTRODUCTION .

Scientific activity during the period covered, July 1993 to June 1996, continued on high levels. The interpretations of the observations achieved during the spacecraft flybys of comets Halley and Grigg-Skjellerup still comprise a large number of publications. New missions to comets 81P/Wild 2 (Stardust, NASA Discovery Program) and 46P/Wirtanen (Rosetta, ESA cornerstone mission) were approved. The impact of D/Shoemaker-Levy 9 (SL9) into Jupiter in July 1994 triggered a major effort of coordinated observations. In a similar way the detection of many objects beyond the orbit of Neptune (Trans-Neptunian Objects) influenced observational programs leading to first estimates of the population in the Edgewood-Kuiper belt. The relation between comets and asteroids became a focus of interest. The possible hazards by small bodies crossing Earth's orbit continue to be of interest to the public and trigger international programs of observations. Comet Hale-Bopp (C/1995 O1) approaching the sun promises to become an exceptionally bright object. About half of the papers published in the period of this report are referenced.

4.2. NUCLEUS PROPERTIES, ORIGIN, AND EVOLUTION

The most impressive results came from the splitting of SL9, the discovery of dozens of Kuiper belt objects (Jewitt and Luu 1995), sophisticated observations of cometary nuclei with modern telescopes in different spectral ranges (Festou *et al.* 1993a), and modeling efforts mainly based on continued analysis of Giotto and Vega data, ground based measurements, and laboratory experiments (Festou *et al.* 1993b). A target of special interest was C/Hyakutake which approached Earth to 0.1 AU. The interpretation of the observational database is still in progress. Basic questions about the origin and evolution of comets and the Solar System have been addressed by several scientific activities (Bailey, 1996). New information has been acquired on the nature of the Oort cloud (Weissman, 1996) and the Kuiper belt (Luu, 1994). The relationship between comets and asteroids (Jewitt, 1996) and comets and planets (Owen and Bar-Nun, 1996), including the problem of potential hazards for the Earth, has been investigated (Gehrels (ed.) 1994). However, fundamental problems of cometary research such as the structure and physical properties of nuclei remain unsolved or have been answered controversially.

The splitting of SL9 by tidal forces (Scotti and Melosh, 1993; Sekanina *et al.*, 1993) and the collision of the fragments with Jupiter were without doubt the most spectacular events of the period. The interpretation of numerous observations from the ground (West *et al.*, 1995) and from spacecraft (Weaver *et al.*, 1995; Rettig *et al.*, 1996) give evidence on the size, structure, and density of the nucleus. Using different models, diameters of the parent body ranging from 1.5 to 10 km were derived (Scotti and Melosh, 1993; Sekanina, 1995; Solem, 1994; Chernetenko and Medvedev, 1994). Analyzing the mutual gravitation of the fragments Solem (1995) and Asphaug and Benz (1996) found a density of about 0.5 g cm^{-3}, consistent with a quite porous nucleus. Comparing the forces of splitting with the tidal forces in Jupiters gravitational field, the tensile strength can be estimated. Melosh (1995) gives an upper limit of about 100 Pa, in agreement with a rough theoretical estimation based on calculations of molecular interactions. Starting from a 3D smooth particle simulation, Asphaug and Benz (1996) concluded that SL9 is nearly strengthless. This is in support of a comet composed of gravitationally bound agglomerates (rubble pile model), but the calculations are based on some special assumptions regarding the figure of the comet.

Two main populations of comets exist: the Kuiper belt and the Oort cloud (Kresák, 1994). Starting with the discovery of the trans-Neptunian object 1992 QB1 (Jewitt and Luu, 1993), investigation of the Kuiper belt has become a new frontier of cometary science. About 36 Kuiper belt objects (KBOs), up to 250 km, have been found, mostly from a survey on Mauna Kea (Jewitt *et al.*, 1996) while statistical evidence for small objects was obtained with the Hubble Space Telescope (HST) (Cochran *et al.*, 1995). The KBOs fall into at least two distinct dynamical categories. Some have perihelia far outside the orbit of Neptune and so are relatively protected from strong gravitational perturbations. They have low eccentricities and inclinations. Slow orbital evolution causes some of these objects to become Neptune-crossing (Centaurs) over time scales of billion of years (Duncan *et al.*, 1995). Therefore it is widely suggested to incorporate the known Centaur objects, including Pluto, in the Kuiper belt family. Other KBOs fall in or near the 3:2 mean motion resonance with Neptune. They have eccentricities up to 0.3 and inclinations up to 30°. Stern (1995) found that collisional evolution is important in the Kuiper disk, suggesting that the original mass in the 30-50 AU region must have been much higher to form the known KBOs.

Several other comets have been also extensively investigated. Meech *et al.* (1993) derived a maximum nuclear radius of 15.4 km for 29P/Schwassmann-Wachmann 1 (SW1), considerably smaller than thought before. The rotational state of SW1 is characterized by two periods of 14.0 and 32.3 h. From radio emissions Crovisier *et al.* (1995) inferred a CO production rate of 5×10^{28} s^{-1}. From mid-infrared observations of 109P/Swift-Tuttle, Fomenkova *et al.* (1995) determined a radius of 15 km and a rotational period of 67.5 h. The direct detection of the nucleus of comet 4P/Faye by high resolution measurements with HST yielded a rather spherical body with a mean radius of 2.68 km (Lamy and Toth, 1995). Interpretation of CCD-images of P/Levy 1991 XI by Fitzsimmons and Williams (1994) implies a spin period of 8.34 h, an elongated nucleus with a mean effective radius of less than 8.2 km, and a density larger than 200 kg m^{-3}. Because of the unfavorable observational conditions, new data for the Rosetta target, 46P/Wirtanen, are rare. A summary of observations provided by Jorda and Rickman (1995) indicates a radius of 1.8 km and an H_2O production rate of 4×10^{28} s^{-1} at perihelion. Luu (1993b) presented CCD-spectra of five comets at large heliocentric distances and five cometary nucleus candidates. The results show that cometary nuclei are spectrally diverse, with a range that is greater than hitherto suspected. The chemical composition of cometary nuclei remains an open question. Some facts about the present stage of research were presented by Crovisier (1994) and Greenberg and Shalabiea (1994).

Some new splittings and outbursts of comets have been reported. Chen and Jewitt (1994) found from their systematic CCD-imaging program that 3 comets in a sample of 49 split. They estimate a mean splitting probability of 0.01 per year per comet and conclude that splitting may be an important destruction process of cometary nuclei. Meech *et al.* (1995) presented CCD observations of comet Wilson 1987 VII indicating that it split into two fragments. A detailed analysis showed that the time of splitting is consistent with an observed outburst in October 1987 at about 3 AU from the Sun. Kidger (1993) investigated the lightcurve of the outburst of 97P/Metcalf-Brewington. Its absolute magnitude brightened at least 11 magnitudes. Crovisier *et al.* (1996) reported the splitting of 73P/Schwassmann-Wachmann 3. The cause of splitting and outbursts remains puzzling; no special mechanism could be clearly identified yet.

The origin and dynamical evolution of comets have been widely discussed. Weidenschilling (1994) explained the observed sizes and structure of cometary nuclei by a two-stage process: collisional coagulation in the solar nebula followed by gravitational instability of a layer of macroscopic bodies. A recent review about the dynamics of comets was given by Fernández (1994). He argued that the Oort cloud was substantially perturbed by passing stars, tidal forces of the galactic disk, and giant molecular clouds. Weissman (1996) considers the dynamical consequences of stars passing through the Oort cloud. Tancredi (1994), Tancredi *et al.* (1994), and Banaszkiewicz and Rickman (1996) coupled physical and dynamical models and applied Monte Carlo simulations and kinetic theory, respectively, to study the evolution of Jupiter family comets. They analyzed the correlation between activity and orbital changes. Emel'yanov and Bailey (1995) explained the observed 1/a-distribution in the light of improved understanding of the dynamical evolution of long-periodic (LP) comets. Salitis (1995) and Zheng *et al.* (1995) investigated the transformation of LP into short-period comets. The long-term dynamical behavior of short-period comets was calculated by Levison and Duncan (1994) and Chambers (1995). Yeomans (1994) published a review about nongravitational forces. Some authors investigated these forces in detail. Sekanina (1993) refined the theoretical basis of nongravitational motions. Bolatto *et al.* (1995) demonstrated that nongravitational forces dominate over planetary perturbations in the long-term evolution only for LP comets approaching the Sun to distances < 0.1 AU. Yau *et al.* (1994) investigated the action of nongravitational forces on comet 109P/Swift-Tuttle and found they appear to be negligible. Benest and Gonczi (1994) and Kulikova and Myshev (1995) analyzed the orbital evolution of comets using stochastic methods. An interesting analogy to a cometary cloud around another star of the Milky Way, β-Pictoris, was discussed by Beust and Morbidelli (1996).

Despite the lack of strong new observational data for cometary nuclei, large efforts to improve the existing models have been made. The images of comet 1P/Halley during the Giotto (Keller *et al.*, 1995) and Vega (Szegö *et al.*, 1995) flybys were published in final form. The interpretation of data on Halley by sophisticated models proceeds. Combining a 2-D gas dynamic model with a 1-D thermal model of the nucleus, Knollenberg *et al.* (1996) found that a dust-to-gas ratio of 1 to 2.5 and a size distribution dominated by large grains can explain jet features observed with the Halley Multicolour Camera (Keller *et al.*, 1995). The interpretation of the cometary simulations of the KOSI experiment was completed (Benkhoff *et al.*, 1995; Kührt *et al.*, 1995; Thiel *et al.*, 1995). Benkhoff and Huebner (1995), Orosei *et al.* (1995), and Espinasse *et al.* (1993) solved the heat and mass transport within a multicomponent porous icy body. They studied the dust and gas emission from the body and found a chemical differentiation in the subsurface layers. Skorov and Rickman (1995) simulated the gas flow in a porous cometary mantle using Monte Carlo methods and found deviations from the normally assumed Maxwellian velocity distribution of the gas molecules. Kührt and Keller (1994, 1996) studied the development of cohesive surface crusts on comets. They concluded that dust is the main fraction in cometary nuclei and that there are strong chemical and structural inhomogeneities. Möhlmann (1995) related cometary activity zones to debris zones between building blocks during the impact growth of comets. Möhlmann (1994) argues from observational facts and modeling efforts that regolith may have been formed on the surface of comets. The crystallization front in a porous amorphous ice medium was studied by Prialnik (1993). She identified this process as a possible source of activity of far distant comets. Owen and Bar-Nun (1995) performed laboratory studies of the trapping of different gases in amorphous ice and suggest that this could be an effective mechanism to deliver volatiles to the inner planets by comets.

The importance of comets for the development of the biosphere on the Earth (Delsemme, 1995; Owen and Bar-Nun, 1996) and the potential risk of collisions of comets with the Earth have been discussed in several papers (Gehrels (ed.) 1994).

4.3. DUST COMA AND TAIL

During the flyby of 26P/Grigg-Skjellerup the OPE experiment onboard Giotto probed the dust coma environment from the distance of first contact at around 17,000 km towards closest approach within 200 km tailward of the nucleus and gave evidence for changes of the optical properties of the grains between the dark and sunny sides of the coma and in the inner coma (Levasseur-Regourd *et al.*, 1993). An analysis of the slopes of the OPE radial brightness profiles supports an earlier dust environment model for that comet (Fulle *et al.*, 1994).

By narrowband photometry of 85 objects during 1976-1994, a quantitative classification scheme for comets was established with respect to dust-to-gas ratio and dust colors (A'Hearn *et al.*, 1995).

The typical reddening of the dust coma by a few percent per 1000 Åand a low ratio of (CN-)gas to dust was found in comet 4P/Faye while the newly injected comet Zanotta-Brewington 1992 III showed solar colors with a high gas-to-dust ratio (Jorda and Rickman, 1995).

For comet 109P/Swift-Tuttle a rotational period of 2.795 d was derived from dust and gas jets in the coma due to 3 active regions on the nucleus (Böhnhardt and Birkle, 1994). The daily activity of the highly collimated dust jets culminated sharply after local meridian passage of the sources. Imaging polarimetry of the same comet revealed a higher polarization degree than for typical dusty comets and a dust emission velocity of 660 m s^{-1} (Goldberg and Brosch, 1995). In the dust jets a 4% higher degree of polarization than in the surroundings was measured (Eaton *et al.*, 1995). For pre-perihelion times, at least 90% of the 7×10^{10} kg dust produced by P/Swift-Tuttle was injected into the Perseid stream (Fulle *et al.*, 1994).

From wide-field Schmidt telescope images of the antitail of comet Levy 1990 XX, an ejection velocity for submicron-sized dust of 120 m s^{-1} at and 30 m s^{-1} before perihelion as well as a maximum dust mass loss rate of 3×10^4 kg s^{-1} shortly before perihelion was deduced by Monte Carlo modeling of the dust tail (Cremonese and Fulle, 1994). Less than 2% of the dust of comet Levy came into bound orbits.

Besides the detailed description of the dust coma around the SL9 nuclei from the HST images (Weaver *et al.*, 1994; 1995), broadband colors of the SL9 dust were determined in the Gunn (Chernova *et al.*, 1995) and Johnson (Trilling *et al.*, 1995) systems showing a reddening effect with increasing distance from the nucleus for most of the fragments. The detection of dust streams from SL9 with the Ulysses spacecraft could not undoubtedly be verified (Grün *et al.*, 1994).

Observations of the inner coma of comet Hale-Bopp (C/1995 O1) at 7.2 AU indicate changes in the wavelength dependence of the observed flux in the inner coma at the initiation of major jet events (Kidger *et al.*, 1996).

Broadband photometry at 1-240 μm obtained for comet Austin 1990 V with the COBE satellite detected a structured, 6°-long, dust tail with grains at about 310 K (graybody) and a total mass of 7×10^{10} kg (Lisse *et al.*, 1994). IRAS LRS spectra ($7.7 - 23\mu$m) of comets 9P/Tempel 1 and 10P/Tempel 2 showed slightly extended sources produced from dust close to radiative equilibrium temperature, but no silicate emission could be detected (Lynch *et al.*, 1995).

A near-perihelion outburst of comet 1P/Halley observed in the thermal IR produced dust which may have been responsible for tail streamers seen in Schmidt exposures of 22 Feb. 1986 (Gehrz *et al.*, 1995). It is suggested that jets released a significant amount of small grains which may account for the variable infrared behavior observed in this comet. Further observational evidence for dust being the origin of the extended source of gas production inside the coma of P/Halley is provided from spacecraft experiments for H_3CO^+ (via H_2CO) and for C_2 (Meier *et al.*, 1993; Rousselot *et al.*, 1994). Modeling scenarios and further discussion of this phenomenon can be found in Samarasinha and Belton (1994) and Crifo (1995). The orbital stability of large particles up to decimeter size around cometary nuclei is studied using a closed solution for the dust motion under radiation pressure (Richter and Keller, 1995).

The elongated shape of coma isophotes outside about 10^4 km can be related with dust fragmentation producing a large number of particles highly sensitive to radiation pressure acceleration from a relatively small amount of heavy low velocity grains (Combi, 1994).

The collimation of dust jets observed by the HMC at comet 1P/Halley is explained by emission from active regions with inbred inactive patches (Keller *et al.*, 1994). A model of multiple light scattering at grains was used to examine dust structures observed *in situ* in a cometary coma (Chick and Gombosi, 1993).

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Fragmentation of electrically charged grains in cometary comae is claimed to be involved in the production of S_2 gas observed in comets (Vanysek, 1994), although alternative explanations *via* gas reaction synthesis may also be possible (Saxena and Misra, 1995).

An analysis of $8 - 13\mu m$ features of cometary dust by means of spectra from the Trapezium, IDPs, and laboratory mineral samples as well as model calculations for small grains concluded that there is no unique cometary silicate (Hanner *et al.*, 1994). A mixture of olivine- and pyroxene-type grains provides a satisfactory fit to the $10\mu m$ band in comets 1P/Halley and P/Levy 1991 XI when using new laboratory measurements of different silicate substrates of submicron grains (Colangeli *et al.*, 1996). The assumption that amorphous ice formed routinely on cometary grains at temperatures below 80 K has to be reexamined in view of new IR spectra of laboratory dust experiments (Moore *et al.*, 1994).

4.4. GAS COMA AND PHOTOCHEMISTRY

Analysis of data on comet 1P/Halley continued. Further investigation on the spacecraft data led to new results on the presence and abundance of several species in the inner coma. The analysis of the Giotto NMS data resulted in detailed information on the extended formaldehyde source (Meier *et al.*, 1993), on the abundance of ammonia (Meier *et al.*, 1994) as well as those of methanol and hydrogen sulfide (Eberhardt *et al.*, 1994). The D/H and $^{18}O/^{16}O$ isotopic ratios in water were also re-determined (Eberhardt *et al.*, 1995). Numerical simulations by Samarasinha and Belton (1994) give an alternative explanation for the extended source of CO found from Giotto NMS measurements. Evidence for a quasi-point source of the CH_2 radical indicating the presence of heavy organic molecules was found in the IMS-HIS measurements (Altwegg *et al.*, 1994). The radial OH distribution in the inner coma was determined from Vega 2 TKS data (Rousselot *et al.*, 1993). Vega 2 TKS data also led to the detection of a polycyclic aromatic molecule (Moreels *et al.*, 1994) and the study of the evolution of the C_2 spectrum provided evidence for a diffuse source (Rousselot *et al.*, 1994). The evolution of the C_2 spectrum with cometocentric distance was also studied for comets 24P/Schaumasse and 10P/Tempel 2 (Rousselot *et al.*, 1995a). The excitation mechanism of the C_2 Swan bands was investigated (Rousselot *et al.*, 1995b). Phenanthrene was identified in the inner coma (Brechignac, 1995).

Combi *et al.* (1994) used a time-dependent Monte Carlo model to reproduce the highly variable CN profiles in comet Halley resulting from a 7.37-day periodic variation in the CN production rate. The spatial distributions of gaseous coma species and their relations to the nuclear rotation were further investigated by Cochran and Trout (1994). Pre- and postperihelion abundances of gas and dust in comet 1P/Halley were derived from photometrically calibrated spectra (Womack *et al.*, 1994), while surface photometry was conducted (Sizonenko, 1994) and spectra in the near-IR region were discussed (Esipov *et al.*, 1994). Fink (1994) reports on observational confirmation for water evaporation controlling 1P/Halley's activity between 0.73 and 2.52 AU.

Numerous observations of comet 109P/Swift-Tuttle were evaluated. The comet was studied both with UBV photometry (Padalia *et al.*, 1993) and photographically (Joshi *et al.*, 1995) and spectrophotometric observations were used to derive the column densities and production rates of several coma species (Sanwal *et al.*, 1993; 1994). The OH production rate was determined from the OH radio lines, which exhibited unusually high blueshifts reflecting the presence of strong jets in the coma (Bockelée-Morvan *et al.*, 1994a). Time variable coma structures were morphologically investigated by Böhnhardt and Birkle (1994) and a quantitative study of the spatial and temporal variability of several neutral coma species was performed by Schulz *et al.* (1994).

Organic species were detected in Swift-Tuttle by infrared and submillimeter techniques. The abundance of methanol was reported from infrared observations to be either $7 \pm 1\%$ (Hoban *et al.*, 1993) or $\sim 5\%$ (Davies *et al.*, 1993). Davies *et al.* (1993) also report on indications for other organics in their spectra. The methanol abundance derived by Hoban *et al.* (1993) was later revised to $4.3 \pm 0.5\%$ by DiSanti *et al.* (1995) who also suggest CH_2 or CH-X vibrational stretching in some as yet unidentified compound. Methanol, formaldehyde, and HCN were detected in the submillimeter range and their production rates were derived (Bockelée-Morvan *et al.*, 1994b). HCN was also detected by Wootten *et al.* (1994) and a cometary water ice isotopic ratio $[D]/[H] < 2.5 \times 10^{-3}$ was inferred from the HDO upper limit. Tozzi *et al.* (1994) reported the detection of the OH Meinel system in Swift-Tuttle, whereas Brown *et al.* (1995) announced the non-detection of this system in their data obtained of this same comet.

D/Shoemaker-Levy 9 was spectroscopicly observed to search for gas emissions, which could however not be detected. Upper limits were derived for the water production rate by Weaver *et al.* (1994a; 1995) and for the CN production rate by Cochran *et al.* (1994) and by Stüwe *et al.* (1995). A review on the chemical composition of SL9 was given by Crovisier (1995).

Detection of the J(2-1) line of CO at submillimeter wavelengths in distant comet 29P/Schwassman-Wachmann 1 during an outburst provided the first direct evidence that sublimation of volatiles can drive activity of distant comets (Senay and Jewitt, 1994). Observations of the J(2-0) and (1-0) lines of CO with high spectral resolution were used to infer kinematics of the coma, cold kinetic and rotational temperatures and a CO production rate (Crovisier *et al.*, 1995).

Comet Hale-Bopp (1995 O1), heading towards its perihelion and extraordinarily bright at large heliocentric distances, was studied with radio techniques. A very large production of CO was observed, suggesting CO to be the driver for the early activity of this comet (Jewitt *et al.*, 1996; Biver *et al.*, 1996). The photometric evolution of Hale-Bopp at large r_H was examined by Kidger *et al.* (1996). CO Cameron band emission was detected in comet 103P/Hartley 2 with HST/FOS (Weaver *et al.*, 1994b).

Emission from the negative carbon ion C_2^- was discovered in comet Scorichenko-George 1990 VI (Churyumov *et al.*, 1993).

Methanol production rates were determeind from infrared observations of comets Austin 1990 V and Levy 1990 XX (Bockelée-Morvan *et al.*, 1994) and the contribution of methanol to the $3.2 - 3.6\mu$m emission feature in comets was investigated (Bockelée-Morvan *et al.*, 1995). Hoban (1993) reports on serendipitous images of methanol in comet Levy 1990 XX.

Several comets were photometricly studied. A'Hearn *et al.* (1995) present the results of their survey of 85 comets with narrowband photometry showing that half of the Jupiter-family comets are depleted in the C_2 and C_3 abundances. Reviews on the current state of knowledge of similarities and differences in the composition of comets (Schleicher, 1994) and on molecular abundances in comets (Crovisier, 1994a) were given. A tabulation of comet observations was published by Cochran and Schleicher (1993). From two-dimensional CCD photometry the production rates, lifetimes and velocities of C_2, C_3 and CN were determined for comet Wilson 1987 VII (Schulz *et al.*, 1993). In addition photometric studies of 23P/Brorsen-Metcalf (Svoren, 1994), 43P/Wolf-Harrington (Schleicher *et al.*, 1993), Austin 1990 V (Waniak *et al.*, 1994), 4P/Faye (Gil-Hutton and Licandro, 1994), Levy 1990 XX (Magdziarz *et al.*, 1995), Shoemaker-Levy 1992 XIX (Chernova *et al.*, 1994), and Kohoutek 1973 XII (De Almeida, 1996) were conducted leading to production rates of several coma species in these comets. The visual light curve of 71P/Clark's 1984 apparition was analyzed (Morris, 1995).

Cometary spectra were reviewed by Feldman (1994). Fink and Hicks (1996) reported on a spectrophotometric survey of 39 comets. The CS band intensities, column densities and production rates were calculated for 15 comets (Sanzovo *et al.*, 1993). The spectroscopic observations of comet 24P/Schaumasse resulted in the production rates of several cometary species (Churyumov *et al.*, 1994b; Turner and Smith, 1995) as did the spectroscopic study of 23P/Brorsen-Metcalf (Korsun and Lipatov, 1993).

Echelle spectra of the H_α emission in comets Austin 1990 V and Levy 1990 XX show the presence of high-velocity hydrogen in both comets (Brown and Spinrad, 1993).

A model to compute fluorescence spectra of the stable isotopes of CN in cometary comae was established by Kleine *et al.* (1994) providing a methodology to compute accurate rotational line fluorescence efficiencies. Photodestruction rates for cometary parent molecules were presented by Crovisier (1994b).

The connection between solar flux variability and the lifetimes of cometary H_2O and OH were modeled and compared to comets Bradfield 1979 X and Austin 1990 V (Budzien *et al.*, 1994).

A general physicochemical model of the inner coma of active comets was developed by Crifo (1995) and the formation of a near-nucleus coma by the interaction of dusty gas jets was studied by Crifo *et al.* (1995).

4.5. PLASMA

The investigations of cometary plasma physics during the period between 1993 and 1995 have concentrated on three main areas. First, some definite results from the ion and neutral mass spectrometer experiments on the Giotto probe to comet 1P/Halley in 1986 had finally been reported by the instrument groups after detailed data analyses. Second, the observational results from the Giotto encounter with comet 26P/Grigg-Skjellerup on July 10, 1992 provided another opportunity to compare the plasma environments of comets with different outgassing rates. Third, the atmospheric impacts of SL9 with Jupiter in July 1994 created a lot of excitement connected to the possible magnetospheric effects. Last

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but not least, significant progress has been made in ground-based observations and computer simulations of cometary plasma dynamics. Some of the major results are highlighted below.

4.5.1. *Comet 1P/Halley*

In the continuing investigations of the spacecraft observations of comet Halley, Flammer (1993) and Puhl-Quinn and Cravens (1995) employed a 1-D hybrid code to simulate the formation of the magnetic field-free cavity. These authors found that the steep magnetic ramp and density enhancement are related to the existence of a recombination front in which the thermal pressure gradient force plays an important role in the force balance. Eberhardt and Krankowsky (1995) and Häberli *et al.* (1995) used the ion composition measurements in the inner coma of comet Halley to deduce that the observed sharp discontinuity in the ion number density (or pileup region) at a cometocentric distance of about 10,000 km is closely related to the radial variation of the electron temperature. This is because the electron dissociative recombination rate strongly depends on the electron temperature. Inside the magnetic field-free cavity the electron temperature is as low as 100 K; the observed ion number density profile is consistent with a change of the electron temperature from a value of about 900 K at 8,500 km to about 20,000 K at 11,000 km (Eberhardt and Krankowsky, 1995). Ip (1994) invoked the possible time variation of such plasma density boundary as a source mechanism for the generation of narrow ion rays in the cometary plasma tails. A similar theoretical model of thermal instability was constructed by Milikh and Sharma (1995).

Altwegg *et al.* (1994) examined the mass/charge group of 12-16 amu/e from the Ion Mass Spectrometer on Giotto and concluded that the methane production rate relative to that of water is $< 1\%$ in comet Halley. They also found that a quasi-point source is required for CH_2 (from organic molecules?) with a source strength of about 0.27%. A thorough survey of the ion population between 1,300 km and 230,000 km in the mass range of 16-19 amu/e in the coma of comet Halley was given by Altwegg *et al.* (1993). The ion bulk flow and temperature profile of the water group ions are reported in the same work. The same data set was used by Balsiger *et al.* (1995) to calculate the D/H ratio $(3.08 + 0.38/ - 0.53 \times 10^{-4})$. This means that the D/H ratio of Halley is significantly higher than the average value of telluric water of 1.6×10^{-4}.

Rème *et al.* (1994) reexamined the electron and heavy ion measurements at comet Halley in a search for possible evidence of a cometopause at about 1.6×10^5 km which was first detected by the plasma experiment on the Vega 2 spacecraft as a sharp boundary in ion chemical composition. From comparison of the inbound and outbound Giotto observations, these authors concluded that such plasma structure could not be of permanent and steady nature. The evolution of the velocity distribution of the water group ions from large cometocentric distances to the midcometosheath $(10^5 - 2 \times 10^5$ km) was studied by Huddleston *et al.* (1993a). These authors traced the scattering effect of the Alfven waves, the speed of which was a significant portion of the local plasma bulk flow. Puhl *et al.* (1993) made a detailed theoretical study of the thermalization process of cometary ions in the same region. They found that the cometary ion distribution evolves from unthermalized, shell-like to Maxwellian with the transition zone being at about 4×10^4 km, inside which ion-neutral and Coulomb collisions will play the dominant role in producing a thermal core of the cold ion velocity distribution. The excitations of hydromagnetic waves and plasma turbulence in the outer cometary comas are still very much topics of interest. Analyses were given by Glaßmeier *et al.* (1993), Karimabadi *et al.* (1994), and Lakhina (1995). Finally, further analyses of the magnetic field structures in different regions of comet Halley had been carried out by Israelevich and Ershkovich (1993, 1994) and Israelevich *et al.* (1993, 1994, 1995).

4.5.2. *Comet 26P/Grigg-Skjellerup*

The Giotto spacecraft encountered the weakly outgassing comet, 26P/Grigg-Skjellerup (G-S), on July 10, 1992. Because most of the functioning instruments after the high-speed flyby of Comet Halley were plasma experiments, the main results of the G-S encounter are therefore in the area of comet-solar wind interaction. Even though the gas production rates of comets Halley and G-S differed by almost two orders of magnitude at the time of the Giotto measurements, the general structures of the cometary bow wave/shock and large-amplitude electromagnetic plasma waves appeared to be very similar (Glaßmeier and Neubauer, 1993; Neubauer *et al.*, 1993; Rème *et al.*, 1993; Flammer and Mendis, 1993). One new feature found in the plasma measurements has to do with the nongyrotropy of the water-group ions (Coates *et al.*, 1993). Such a nongyrotropic distribution was caused by the large density gradient of implanted ions in the coma of G-S which could in turn excite left-hand polarized Alfven waves with frequencies close to the water-group ion gyrofrequency (Motschmann and Glaßmeier, 1993; Cao *et al.*, 1995). Huddleston *et al.* (1993b; 1993c; 1993a) examined the evolution of the velocity diffusion process by comparing the measurements from the Giotto Johnstone plasma analyzer to a theoretical model. The electron measurements from Rème *et al.* (1993) showed that strong oscillation of the electron fluxes could reach a peak-to-valley ratio as high as 20:1 at 35 eV energy. A "mystery" region characterized by high fluxes of hundreds of eV electrons as with comet Halley could be identified. Large variations in the ion fluxes were also detected by the Ion Mass Spectrometer even though most of the ions detected by the sensor might in fact be solar wind protons instead of the water-group ions of cometary origin (Goldstein *et al.*, 1994). This observation could be interpreted in terms of a narrow pitch angle distribution of the protons. Other specific theoretical problems related to wave excitation in the coma of G-S were also addressed by a number of authors (Shevchenko *et al.*, 1995; Verheest and Lakhina, 1994).

4.5.3. *Comet D/Shoemaker-Levy 9*

The atmospheric impacts of SL9 with Jupiter in July 1994 had unexpectedly opened up a new field having to do with plasma interactions of comets with planetary ionospheres and magnetospheres. Before the comet impacts, a number of theoretical predictions were made anticipating the possible magnetospheric effects which might be detectable from the ground or in space. The emphases were mostly on the nature of dust-plasma interactions (Dessler and Hill, 1994; Herbert, 1994; Ip and Prangé, 1994) and on the possibility of generation of electric current systems coupling the cometary coma to the Jovian ionosphere (Farrell *et al.*, 1994; Ip and Prangé, 1994; Kellogg, 1994). In the latter case, a scenario was developed in which decimetric radio waves might be triggered by the presence of a strong field-aligned current flow.

4.5.4. *General*

Large-scale events in the ion tails continued to be a focal point of ground-based study. Farnham and Meech (1994) compared the plasma tail features in four bright comets. These authors concluded that the cause of the ion tail disconnection event might be multi-folded and not necessarily limited to one single mechanism. On the other hand, correlations of the wide-field photographic images of comet Halley taken in March and April of 1986 with the solar wind measurements from the interplanetary spacecraft IMP-8 have led Yi *et al.* (1993, 1994a, 1994b) to the conclusion that the observed disconnection events were most likely produced by sector boundary crossing or interplanetary field reversals, and not due to other effects such as a compression region of the solar wind. Time-dependent codes have been employed to simulate the response of cometary ion tails to interplanetary shocks and interplanetary magnetic field structures by Wegmann (1995) and Rauer *et al.* (1995), respectively. The work of Rauer *et al.* (1995) showed that a sudden rotation of the interplanetary magnetic field direction by 90° will lead to the formation of a pair of symmetric tail rays folding towards the central axis as often observed. Wegmann's study traced the temporal evolution of a cometary ion tail after being hit by an interplanetary shock and he found that the phenomenon is quite similar to a disconnection event. The real physical cause of the ion tail disconnection events thus appears to remain a matter of debate to be clarified by further coordinated observations and numerical modeling. From this point of view, new computational techniques as developed by Gombosi *et al.* (1994) which can map the MHD structures of the cometary ionosphere and magnetotail at different spatial scales are sure to play an increasingly important role. The mass-loading effect of the cometary ions had been incorporated into an analytical multifluid model by Zank *et al.* (1994) to examine the formation of the cometary bow shock. Even though kinetic effects were not included, this one-dimension treatment produced estimates of the shock thickness, location and other plasma parameters which were in good agreement with observations. Besides the above-described picture of comet-solar wind interaction, it is crucial to remember that cometary comas and ionospheres are still strange places in which many unexpected, novel effects could take place. An example is the explosive ionization mechanism in the inner coma due to interaction of the coma gas with interplanetary dust particles or dust-dust collision as proposed by Ibadov (1995). There might still be many surprises just around the corner!