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COMMISSION 15: PHYSICAL STUDY OF COMETS AND MINOR PLANETS

(ETUDE PHYSIQUE DES COMETES ET DES PETITES PLANETES)

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1. Introduction

The present report of Commission 15 has been prepared by A. Cellino with the help of A. Barucci and E. Tedesco for the asteroid part and by G. Cremonese supported by M. T. Capria and L. Jorda for the comet part. The work was coordinated by our Commission Secretary G. Cremonese (who also supports the Commission's webpage). The two sections were compiled rather independently and hence follow different styles in referencing appropriate papers. Due to some unforeseen circumstances the time for assembling particularly the comet part was very short. This part is therefore less extensive than it used to be in the past.

Scientific activity in the field has been very intense in the past three years, and led to publication of a large number of papers. This is a good indication of the activity in Planetary Sciences, in particular that concerning Small Bodies. On the other hand, such an impressive amount of papers constitutes a problem when the ongoing activity is to be summarized. For this reason the report does not include a comprehensive bibliography. The comet section, however, includes a list of the papers cited herein. References are cited in the text by year and, in the case of the asteroids, also include a topic number and sequential number indicating the location of each paper in a bibliographic database created by the Minor Planet Working Group. Thus (1999, T06-011) refers to the 11th paper (published in 1999) in the 6th topic defined in the database. The comprehensive list of references (including separately the asteroid bibliographic database described above) compiled using the ADS is available from the Commission 15 web page, which can be reached via a link from the IAU home page (http://www.iau.org).

The President would like to thank his colleagues who participated in the compilation of this report for the supportive co-operation on very short notice.

2. Asteroids

In this section, papers related to asteroid physical studies and their connections with meteorites are briefly summarized.

This report is based upon a compilation of 199 refereed papers published between July 1999 and June 2002.

Using a format similar to that used in the previous transactions, the material is organized into a series of arbitrary categories. In many cases a given paper could have been assigned, in principle, to more than one category. The final choice was at the whim of the database compiler (A. Cellino).

As a general comment, we can say that the last three years have seen a number of very important achievements in the field of asteroid science. Space missions have produced a wealth of exciting new data. The population of near-Earth asteroids has been extensively investigated due to the increasingly wide recognition of the existence of an impact hazard. The role of thermal emission in affecting the rotational and orbital properties of small bodies has been extensively recognized. The physical properties of families and their evolution since the time of their formation has been a hotly debated subject. The discovery of hydration features in the spectra of M-class asteroids has opened exciting new problems. Radar experiments have produced excellent new results at an increasing rate, and both Radar and Adaptive Optics have led to the discovery of many new binary systems among asteroids. These are only a few examples among the many outstanding results obtained since the last IAU GA. A more analytical list of contributions is given in the sections below.

2.1. Size Distributions, Masses and Densities

The computation of asteroid masses from a measurement of the tiny orbit perturbations experienced in case of mutual close approaches is an active field of research. A list of candidates for these measurements has been published by Galád (2001, T01-005). New observational results have been presented by Viateau (2000, T01-002), Michalak (2000, T01-003), Viateau and Rapaport (2001, T01-006), Michalak (2001, T01-007). An assessment of the accuracy limit of modern ephemerides of the inner planets due to the existing uncertainties in asteroid masses was discussed by Standish and Fienga (2002, T01-008).

The problem of the size distribution of the asteroid population, which is poorly known at small sizes below the limit of completeness of current surveys is another hot topic. Campo Bagatin and Petit (2001, T01-004) discussed the possible role of geometric constraints on the size distribution of the fragments produced by events of catastrophic collisions. The possibility that the whole asteroid belt distribution of observable sizes can be fit by multifractal distributions has been investigated by Campo Bagatin et al. (2002, T01-010). From the observational point of view, the first results of a deep asteroid search at thermal IR wavelengths using the ISO satellite was presented by Tedesco and Désert (2002, T01-009).

Advances in the determinations of asteroid masses (also from the discovery of new binary systems) and sizes lead naturally to a better evaluation of asteroid densities. Birlan (2000, T01-001) analyzed the situation at the time of his analysis, and pointed out the problem of the resulting unexpectedly low density of some M-class asteroids, hardly compatible with a metal-rich composition of these objects.

2.2. Photometry, Shapes, Disk-Resolved Images, Rotations, and Pole Orientations

Lightcurve photometry continues to be an active area of asteroid observations and is the basis for most of the research described in this section. New observations were performed by Kiss et al. (1999, T02-001), Pravec et al. (2000, T02-003), Blanco et al. (2000, T02-005), Pravec et al. (2000, T02-006), Denchev (2000, T02-008), Denchev et al. (2000, T02-011), Michałowski et al. (2000, T02-015), Lagerkvist et al. (2001, T02-019) (the latter paper referring to a sample of Cybele asteroids, beyond the borders of the main belt), Davies et al. (2001, T02-020), Angeli et al. (2001, T02-021), Michałowski et al. (2001, T02-022), Riccioli et al. (2001, T02-023). CCD photometry of the detached binary 90 Antiope was performed by Michałowski et al. (2001, T02-030). Lightcurves of four fast-rotating asteroids were obtained by Whiteley et al. (2002, T02-034). The importance of these observations is that the very fast spin periods of these objects indicate that they must be essentially monolithic and held together by solid-state forces. Similar results for a sample of three near-Earth asteroids were also obtained by Pravec et al. (2000, T02-014).

Results of photometric observations devoted to particular objects were published by Pravec et al. (2000, T02-018), who observed the slow rotator 1999 GU_3, and Davies et al. (2001, T02-020), who observed 1998 WU_{24}, an object having orbital characteristics similar to Halley family comets, but showing no recognizable cometary activity. The rotation of 1620 Geographos was studied by Ryabova (2002, T02-032).

Determinations of pole orientation and shape determinations based on lightcurve data were published by Blanco et al. (2000, T02-009). An important result of photometric observations was the discovery in some cases of multiple periodicities, interpreted as evidence of binarity. Papers presenting such discoveries were published for asteroid 1996 FG_3 by Mottola and Lahulla (2000, T02-007), and for asteroid 4197 by Prokof'eva et al. (2001, T02-025).

On the theoretical side, a study of the inelastic dissipation in wobbling objects was published by Efroimsky and Lazarian (2000, T02-002) and Efroimsky (2001, T02-024), while the effects of gravitational interactions on asteroid spin states were analyzed by Scheeres et al. (2000, T02-013). The opposition effect on asteroid brightness was analyzed by Belskaya and Shevchenko (2000, T02-012) and by Shevchenko et al. (2002, T02-031), while a laboratory study of bidirectional reflectance of powdered surfaces observed at different phase angles was performed by Kamei and Nakamura (2002, T02-033). Scheeres et al. (2000, T02-010) studied the problem of estimating asteroid density distributions from shape and gravity information. An interpretation of the distribution of asteroid spin periods, including the presence of fast and slow rotators, was given by Pravec and Harris (2000, T02-016). Rubincam (2000, T02-017) analyzed the likely importance of radiative spin-up and spin-down of small asteroids (YORP effect). The problem of asteroid lightcurve inversion was extensively analyzed by Kaasalainen et al. (2001, T02-026) and Kaasalainen and Torppa (2001, T02-027). Kaasalainen (2001, T02-028) also analyzed the problem of the interpretation of the light curves of precessing asteroids.

Apart from photometry, other techniques were also applied to obtain information on asteroid shapes ad pole orientations. These include speckle interferometry (Ragazzoni et al., 2000, T02-004) and HST observations using the FGS interferometer (Tanga et al., 2001, T02-029).

2.3. Radar, Thermal Infrared, Optical Polarimetry

Radar experiments have been a field in very rapid growth during the last three years. The ideal targets for these observations are near-Earth objects, due to the dependence of radar echoes on the power -4 of the distance of the target object. But also main belt asteroids have been extensively observed. A summary of the radar observations of main belt asteroids from 1980 to 1995 has been published by Magri et al. (1999, T03-001). New observations of asteroid 216 Kleopatra have been performed by Ostro et al. (2000, T03-005), while Ostro et al. (2001, T03-010) presented new radar observations of 288 Glauke. Near-Earth asteroid targets of radar experiments include 1566 Icarus (Mahapatra et al., 1999, T03-002), 2100 Ra Shalom (Shepard et al., 2000, T03-008), 6489 Golevka (Hudson et al., 2000, T03-009), 1998 ML_{14} (Ostro et al., 2001, T03-012), 7335 (Mahapatra et al., 2002, T03-015), 1862 Apollo (Ostro et al., 2002, T03-016), 1999 JM_8 (Benner et al., 2002, T03-018). Radar echo delay experiments provide huge improvements in the determination of asteroid orbits. An analysis of the physical limits of the prediction of collision probability for objects having both optical and radar data was performed by Giorgini et al. (2002, T03-017) in the case of the near-Earth asteroid 1950 DA. Moreover, Yagudina (2001, T03-011) discussed the use of radar observations of near-Earth asteroids in the determination of the dynamical equinox.

In the field of the measurement of the thermal emission of asteroids at mid-IR wavelengths, the ISO satellite has been an important source of new data. Results of ISO observations were presented by Lagerros et al. (1999, T03-004), and by Dotto et al. (2000, T03-006). Mueller and Lagerros (2002, T03-013) discussed the possibility to use asteroids as standard sources at thermal infrared wavelengths for space observatories.

Finally, an additional and revised catalog of asteroid diameters and albedos based on IRAS observations was published by Tedesco et al. (2002, T03-014).

Optical polarimetry is another well-known and important tool for deriving asteroid albedos (and hence, sizes). The polarimetric properties are also interesting *per se*, being determined by the complicated physics determining the interaction of photons with the surface layers of the objects. Results of new polarimetric observations at large phase angles of the near-Earth asteroid 2100 Ra Shalom were published by Kiselev et al. (1999, T03-003). Nakayama et al. (2000, T03-007) presented the results of observations of variations of the degree of linear polarization as a function of varying rotational phase for asteroids 9, 52, and 1036.

2.4. Binaries and Dynamical Families

The discovery of several binary systems among asteroids has been one of the most important achievements during the last three years. Binaries have been discovered by means of very different techniques, including Radar, Photometry and Adaptive Optics. Many binaries have been discovered among the near-Earth asteroid population. In this subsection, we only note a couple of papers, among those published during the last three years. Other papers dealing with binaries are quoted in previous Sections. The first discovery of a binary after the Ida-Dactyl system found by the Galileo probe has been that of Petit Prince, the satellite of 45 Eugenia. This discovery was described by Merline et al. (1999, T04-003). Among the several near-Earth binaries discovered by radar experiments, the object 2000 DP_{107} has been presented by Margot et al. (2002, T04-010).

Asteroid families have been another field of intense activities. Being interpreted as the outcomes of events of catastrophic disruption, families play a very important role in many different branches of modern asteroid research. A study of the size distribution of family members has been published by Tanga et al. (1999, T04-001), who found very steep slopes of the power-laws describing the cumulative size frequencies down to the sizes of completeness of the samples. Cellino et al. (1999, T04-002) analyzed the relationship between size and ejection velocity for family members. A general increase of the maximum possible ejection velocity for decreasing size was found and some preliminary interpretation in terms of collisional physics was presented. The possible noticeable role played by family-forming events in determining the collisional regime in the asteroid belt has been also analyzed by Dell'Oro et al. (2001, T04-007), who analyzed the increase of collision probability in the regions of the belt in which orbital intersections with the swarms of newly created family members are possible. A number of problems affecting the interpretation of family data and their interpretation has been pointed out by Pisani et al. (1999, T04-005). In particular, the apparently high ejection velocities of family members are hard to reproduce by means of hydrodynamical models, as is the phenomena of gravitational reaccumulation of the fragments. The latter problem has been investigated by Michel et al. (2001, T04-008) on the basis of numerical simulations.

More generally, the importance of evolutionary mechanisms affecting the outcomes of family-forming events has been explored by several different authors. Marzari et al. (1999, T04-004) considered the subsequent collisional evolution experienced by family members, whereas Bottke et al. (2001, T04-009) claimed that the apparently high ejection velocity values resulting from the spreading of family members in proper elements space might be due primarily to the subsequent evolution of the orbits under the influence of the Yarkovsky effect. Finally, Knežević and Pavlović (2000, T04-006) analyzed the complex dynamical behavior of the members of the Veritas family, suggesting that this family might be very young.

2.5. Spectra, Taxonomies, and Compositions

Asteroid spectroscopy is a very important tool for deriving information on surface compositions, and also provides the basic data for taxonomic classifications. During the past three years this has been a growing field of asteroid research, taking profit also of better opportunities to extend the wavelength coverage to the infrared. Results of observations performed using the Infrared Space Observatory (ISO) were published by Heras et al. (2000, T05-005) who observed 4 Vesta, and Dotto et al. (2000, T05-009), who observed the asteroids 1, 2, 3, 4 and 52. Preliminary results from the Two Micron All Sky Survey (2MASS) in the J,H,K bands were presented by Sykes et al. (2000, T05-011), and the DENIS program (Deep European Near-Infrared southern sky Survey) has obtained a large amount of data in the I,J,K bands, as shown by Baudrand et al. (2001, T05-018). Spectrophotometric data at thermal infrared wavelengths have been obtained for the near-Earth asteroids 433, 1980 and 3671 by Harris and Davies (1999, T05-002). Important results concerning the discovery of 3 μm hydration features on M-class asteroids have been presented by Rivkin et al. (2000, T05-007). These authors found that more than one third of a large sample of M-class objects show hydration features which are hardly compatible with the commonly accepted interpretation of M-like spectra as diagnostic of a primarily metallic composition. They also found that hydrated objects are prevalent among the larger ($D > 65$ km) M-class asteroids. They proposed to assign these objects to a new taxonomic class (W). The likely presence of OH structural groups in the surface material of five M-class asteroids was also presented by Busarev (2002, T05-022).

A search for the 3.4 μm C-H spectral bands on low albedo asteroids was attempted by Cruikshank et al. (2002, T05-024), but the results indicate that these bands were not present in a set of seven objects.

At visible and near-infrared wavelengths, important observations have been obtained by several authors, including Hicks et al. (2000, T05-004), Mothé-Diniz et al. (2000, T05-013), Manara et al. (2001, T05-015), Fornasier and Lazzarin (2001, T05-017), and Buratti et al. (2002, T05-023). The latter authors presented high resolution spectra of D-class asteroids, and some Saturnian satellites, and found that the spectra of Hyperion and the dark hemisphere of Iapetus are compatible with a mixture of ice and D-class material.

Burbine et al. (2001, T05-014) examined the spectra of three K-class asteroids and found that two of them (221 and 653), belonging to the Eos family, are spectral analogs of the CO3 chondrite Wasson, whereas 599 Luisa, a K-class object close to 5/2 mean-motion resonance with Jupiter, is a spectral analog for the CV3 chondrite Mokoia.

The puzzling discovery of an outer belt asteroid exhibiting spectral reflectance properties similar to those of Vesta and basaltic achondrites has been announced by Lazzaro et al. (2000, T05-008). The origin of this object remains an open question and its existence has important implications on generally-accepted ideas concerning the origin and evolution of main belt asteroids.

Laboratory experiments concerning the temperature dependence of the spectral reflectance properties of mineral assemblages thought to be present on asteroid surfaces was presented by Moroz et al. (2000, T05-012). The results indicate that the interpretation of asteroid spectra must take into account the temperatures of the objects. On the other hand, problems in the interpretation of asteroid spectra due to the likely presence of space weathering were also analyzed by Hiroi and Sasaki (2001, T05-021), while Hapke (2001, T05-016) studied the process of space weathering in a range of heliocentric distances from Mercury to the asteroid belt.

On the theoretical side, the likely effects of early aqueous alteration in bodies of chondritic compositions were analyzed by Wilson et al. (1999, T05-001). Numerical modeling of S-class asteroids was presented by Shestopalov and Golubeva (2000, T05-003; 2001, T05-020). Golubeva and Shestopalov (2001, T05-019) also simulated a reflectance spectrum of the A-class asteroid 446 Aeternitas. Kelley and Gaffey (2000, T05-006) presented a study of the asteroids 9 Metis and 113 Amalthea as a likely genetic pair.

Finally, Fulchignoni et al. (2000, T05-010) presented an extension of their G-Mode asteroid taxonomy, based on a sample of 438 objects.

2.6. Origins, Impacts, Orbital and Collisional Evolution

A great amount of work has been devoted to topics related to the origin and collisional evolution of asteroids, including theoretical and experimental studies of the physics of catastrophic break-up phenomena. Moreover, a great deal of work has been devoted to studying another phenomenon thought to be very important for the orbital evolution of small objects, namely the so-called Yarkovsky effect due to the non-isotropic re-radiation at thermal wavelengths of the absorbed energy input from the Sun.

On the side of more conventional collisional processes, theoretical studies have been published by Davis (1999, T06-001), who analyzed the likely collisional history of 253 Mathilde. D'Abramo et al. (1999, T06-002) studied the reaccumulation of fragments from a catastrophic disruption. Housen and Holsapple (1999, T06-004) analyzed the scale effects in strength-dominated collisions of rocky asteroids. Ryan (2000, T06-006) reviewed the role of numerical modeling in the studies of asteroid fragmentation. Gil-Hutton and Brunini analyzed the likely collisional evolution of the population of Hilda asteroids. Yanagisawa and Hasegawa (2000, T06-011) studied the momentum transfer in oblique impacts, a phenomenon which is of primary importance for the evolution of the spin properties of the asteroid evolution. Toth found that the temporarily enhanced activity of comet Elst-Pizarro might have been due to collisions with a debris cloud possibly associated with asteroid 427 Galene. Campo Bagatin et al. (2001, T06-015) tried to obtain from state-of-the-art numerical modeling some indications about the likely number of rubble piles existing in the main asteroid belt, but they found that no definitive answer can be found on the basis of current knowledge. Wilson and Keil (2001, T06-018) studied the role of impact-generated regolith redistribution in influencing the shapes of the asteroids. Nolan et al. (2001, T06-020) used a numerical hydrocode to simulate collisional events among asteroids, including fragmentation, regolith transport and disruption. Dell'Oro et al. (2002, T06-024) made a quantitative assessment of the importance of inter-family impacts in the early evolution of asteroid families, and found a short, but intense enhancement in the collisional rate just after family formation, which might be important for the development of a regolith layer and the overall crater size frequency distribution on the surfaces of the objects. Harris (2002, T06-025) discussed the possible origin of slow-rotating asteroids. Nesvorný et al. (2002, T06-027) announced the discovery of a very young asteroid family thought to be only about five million years old. Finally, Korycansky et al. (2002, T06-026) performed high-resolution simulations of the impacts of asteroids into the atmosphere of Venus.

Important papers focused on the role of the Yarkovsky effect, were published by Vokrouhlický and Broz (1999, T06-003), Vokrouhlický and Farinella (1999, T06-005), Vokrouhlický et al. (2000, T06-013), Vokrouhlický and Bottke (2001, T06-017), Vokrouhlický et al. (2001, T06-021).

The processes of accretion of asteroidal bodies and the early phases of the history of the asteroid belt was investigated by several authors, including Kortenkamp and Wetherill (2000, T06-007), Franklin and Lecar (2000, T06-008), Nagasawa et al. (2000, T06-009), Chambers and Wetherill (2001, T06-016), Petit et al. (2001, T06-022), Kouchi et al. (2002, T06-023). The so-called Late Bombardment of terrestrial planets by asteroidal bodies was investigated by Dauphas et al. (2000, T06-014).

Finally, an attempt at modelling the likely structure of high porosity asteroids has been presented by Britt and Consolmagno (2001, T06-019). This study was triggered by the growing observational evidence (like 253 Mathilde visited by the NEAR spacecraft) that many asteroids have bulk densities in the 1.3 g/cm^3 range.

2.7. Asteroids Visited (or to be Visited) by Spacecraft

One of the most spectacular achievements of the last three years has certainly been the successful NEAR-Shoemaker mission. After the earlier fly-by of the main belt C-class asteroid 253 Mathilde, the probe approached and entered orbit around the near-Earth asteroid 433 Eros. After a long and successful period of in-orbit operations, NEAR-Shoemaker eventually terminated its mission with a controlled descent to the asteroid's surface on February 12, 2001.

Many papers have been devoted to matters related to this mission, including the first analysis of some of the most spectacular results of the *in situ* investigations of Mathilde and Eros. For Mathilde, an overview of the encounter was published by Veverka et al. (1999, T07-001). Clark et al. (1999, T07-002) analyzed the imaging data of Mathilde to derive a photometric model of this asteroid. Mathilde turned out to have a low albedo (about 0.04 at visible wavelengths) and to be remarkably homogeneous in reflectance across the surface. The most outstanding property of Mathilde is the presence of relatively huge craters. Possible mechanisms to explain the origin of these craters were presented by Housen et al. (1999, T07-003). Several papers have been published describing the Eros encounter. These include those by Clark et al. (2000, T07-005), Trombka et al. (2000, T07-006), Izenberg et al. (2000, T07-007), Cheng et al. (2000, T07-008), Thomas et al. (2001, T07-012), Veverka et al. (2001, T07-014), Asphaug (2001, T07-015), Nittler et al. (2001, T07-017), Sage (2001, T07-018), Acuña et al. (2002, T07-020), Clark et al. (2002, T07-021), Lucey et al. (2002, T07-022), Miller et al. (2002, T07-023).

A paper on Radar constraints on asteroid regolith composition using 433 Eros as ground truth was also published by Magri et al. (2001, T07-019).

In addition to Near-Shoemaker, the Deep Space 1 mission provided another successful encounter with asteroid 9969 Braille. Ground-based photometry and spectroscopy of this object were performed by Lazzarin et al. (2001, T07-011). A paper devoted to the DS1 measurement of the magnetic field of Braille was also published by Richter et al. (2001, T07-009). A model for the rotation and shape of Braille based on DS1 image data was developed by Oberst et al. (2001, T07-013).

As for imminent missions, Scheeres and Marzari published a study of the temporary orbital capture of ejecta from comets and asteroids, as an application to the Deep Impact mission.

Binzel et al. (2001, T07-010) obtained visible and near-infrared spectra of asteroid 25143 (1998 SF_{36}), the planned target for the Japanese MUSES-C sample return mission.

An international observing campaign was organized to determine the physical characteristics of the Rosetta mission asteroids 140 Siwa and 4979 Otawara. The physical parameters of the flyby targets will aid Rosetta mission planners in optimizing the encounter trajectory and science operations planning. The rotational periods of both asteroids was determined (Doressoundiram et al., 1999, T12-015, Le Bras et al., 2001, T12-022): 140 Siwa has a period of 18.495 hours, while 4979 Otawara is a fast rotating object with a period of only 2.707 hours. The phase functions were also obtained for both asteroids, allowing the determination of the H and G parameters. Spectroscopic observations have been carried out to investigate the surface composition of both the targets: the near infrared spectrum of Siwa does not show any spectral feature, which is consistent with a C/P class object, while the spectral classification of 4979 Otawara seems to be a pyroxene and/or olivine-rich S-class similar to ordinary chondrites.

2.8. The Asteroid–Meteorite Connection

Studies of meteorites are believed to be a very powerful tool for understanding the thermal and collisional histories of their asteroidal parent bodies. With this aim, the density and porosity of stone meteorites were investigated by Flynn et al. (1999, T08-002). Britt and Consolmagno (2000, T08-004) analyzed the porosity of dark meteorites in order to infer information on the likely structure of low-albedo asteroids. Keil (2000, T08-005) focused on the evidence of thermal alterations of asteroids from an analysis of meteorite samples. Bland et al. (2000, T08-007) analyzed the evidence of aqueous alterations in meteorites. Evidence of aqueous processes from an analysis of "bleached" chondrules in L and LL chondrites was also found by Grossman et al. (2000, T08-003). The bulk density of ordinary chondrites and implications for the internal structures of their asteroidal parent bodies were investigated by Wilkinson and Robinson (2000, T08-008). Scott et al. (2001, T08-010) proposed some mechanisms for the production of mesosiderites by fragmentation and reaccretion of large differentiated asteroids. A study of oxidation versus reduction during metamorphism of L and LL chondrites were analyzed by Gastineau-Lyons et al. (2002, T08-013) who studied the implications for asteroid spectroscopy. Kring et al. (1999, T08-001) studied extensively a sample of Portales Valley meteorite fragments. A comparative geochemistry of basalts coming from different sources, including HED achondrites thought to have been originated from 4 Vesta, was performed by Ruzicka et al. (2001, T08-009), leading to implications for the origin of our Moon. The post-crystallization reheating and partial melting of eucrite material as a consequence of impact on the crust of 4 Vesta was analyzed by Yamaguchi et al. (2001, T08-011).

Vokrouhlický and Farinella (2000, T08-006) analyzed the overall mechanism of meteorite delivery from the main asteroid belt, while Farinella et al. (2001, T08-012) investigated a possible asteroidal origin of the Tunguska impactor.

2.9. Near-Earth Asteroids

NEOs, their origin and evolution, and their relationship with impact hazards on Earth have been one of the most important fields of activity in the past three years. One of the major fields of investigation has been the determination of the inventory, size and orbital distribution and steady supply of objects from the main asteroid belt. Important papers have been published by Michel et al. (2000, T09-002), Bottke et al. (2000, T09-004), Vokrouhlický and Milani (2000, T09-012), Evans and Tabachnik (2000, T09-013), Tabachnik and Evans (2000, T09-015), D'Abramo et al. (2001, T09-019), Stuart (2001, T09-021), Werner et al. (2002, T09-023).

Another blooming field of investigations has been that related to impact hazard evaluation. Important results in this respect have been published by Ward and Asphaug (2000, T09-003), Milani et al. (2000, T09-009), Dvorak and Freistetter (2001, T09-017), Muinonen et al. (2001, T09-020), Ji and Liu (2001, T09-022). Korycansky et al. (2000, T09-006) also made computations of asteroid impacts in the atmosphere of Venus.

The topic of optimizing sky surveys devoted to the discovery of near-Earth asteroids has been the subject of investigations by Tedesco et al. (2000, T09-005), Boattini and Forti (2000, T09-007), Isobe (2000, T09-011), and Stokes et al. (2000, T09-014). The latter paper was devoted to the Lincoln Near-Earth Asteroid Program (LINEAR), which has been largely responsible for the dramatic growth of the known asteroid inventory in recent years. In addition, Perozzi et al. (2001, T09-016) analyzed the problem of optimizing rendezvous and flyby missions to near-Earth objects.

Some studies were devoted to detailed physical analyses of the properties of single objects, like 1994 GV studied by Sitarski (2000, T09-010) and 1620 Geographos, studied by Hudson and Ostro (1999, T09-001) and Ryabova (2002, T09-024) who investigated the possibility that this object can have associated meteor streams. More generally, a search for meteor showers associated with near-Earth asteroids was carried out by Babadzhanov (2001, T09-018). Drummond (2000, T09-008) analyzed the possibility of identifying near-Earth asteroid streams by using the so-called D discriminant.

2.10. Trojan Asteroids

Trojans play an increasingly important role in modern asteroid science. The properties of single objects have been the subject of some papers, as in the case of 1437 Diomedes, studied by Sato et al. (2000, T10-001) and 624 Hektor, spectroscopically observed by Cruikshank et al. (2001, T10-007).

Many studies have been devoted to models and assessments of the origin, inventory and evolution of Trojans. Important papers in this respect have been published by Jewitt et al. (2000, T10-003), Fleming and Hamilton (2000, T10-004), Skokos and Dokoumetzidis (2001, T10-005), Beaugé and Roig (2001, T10-008), and Michtchenko et al. (2001, T10-009).

The possibility of the existence and detection of Earth's Trojans has been investigated by Wiegert et al. (2000, T10-002), while in the case of Saturn's Trojans an investigation was carried out by Melita and Brunini (2001, T10-006).

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2.11. Miscellaneous Asteroid–Related Publications

Clark et al. (1999, T11-001) analyzed the possible survival of life on asteroids and other minor bodies. Christou (2000, T11-002) explored the possibility of the existence of phenomena of co-orbiting asteroids, and discussed some possible implications. Foschini (2001, T11-003) studied the process of fragmentation of small asteroids in the Earth's atmosphere. Elst (2001, T11-004) raised the question whether we are approaching the end of the era of asteroid discoveries, based on some indications that the discovery rate may be decreasing. Mueller (2001, T11-005) described serendipitous ISO observations of asteroids. Chen and Jura (2001, T11-006) discussed the existence of a possible massive asteroid belt around ζ Leporis. Finally, Lissauer et al. (2001, T11-007) analyzed the effect that the presence of a planet in the asteroid belt would have had on the orbital stability of the terrestrial planets.

2.12. Main Belt: ISO Asteroid Observations

The Infrared Space Observatory (ISO) provided the opportunity to observe asteroids at mid and far infrared wavelengths that are difficult to observe from the ground. Sixteen main belt asteroids were observed. Photometric data was obtained at wavelengths up to 60 microns, low resolution spectroscopy up to 11.6 microns, and high resolution spectroscopy up to 45 microns (Dotto et al. 1999, T12-013, 2000, T12-013, Mueller et al. 2000, T12-025, Barucci et al. 2002, T12-005). Surface temperatures, diameters, and albedos were computed for all objects observed. The interpretation of the spectral features above the thermal continuum has been performed by analyzing the Christiansen peak, reststrahlen, and transparency features in comparison with laboratory spectra of several minerals and meteorites. Relevant results have been obtained in particular in the case of 2 Pallas with the detection on its surface of a mixture of pyroxenes and possible water ice (Dotto et al. 2000, T12-014). In the case of 10 Hygiea, the suggested analogy with the CO3 carbonaceous chondrite meteorite would imply a primitive body which may have started some metamorphism (Barucci et al. 2002, T12-005).

3. Outer Objects of the Solar System: Physical Characteristics

Trojans, Centaurs and Trans-Neptunian Objects (TNOs) probably contain the most primitive and thermally unprocessed material of the Solar System and their study has rapidly evolved in the past few years. These primitive bodies show in general low albedos (Altenhoff et al. 2001, T12-001, Fernandez et al. 2000, T12-018) and red colors. Various observational evidences suggest that much of their surface material is carbon-rich, in the form of complex organic polymers, polycyclic aromatic hydrocarbons, and other macromolecular compounds (e.g., Cruikshank and Khare 2000, T12-011, Khare et al. 2001, T12-021). Some combinations of minerals with elemental carbon of inorganic origin may be able to match the surface reflectance properties of some of these objects, as in the case of Trojan asteroid 624 Hektor observed by Cruikshank et al. (2001, T12-012). The Hektor spectrum, observed up to 3.6 μm, has been matched with a mixture of Mg-rich pyroxene and elemental carbon (a mixture of graphite and amorphous C). Emery and Brown (2001, T12-017) obtained K-band spectra of five Trojans and L-band (3.0-3.5 micron) spectra of two Trojans. They showed the red slope expected for P and D asteroids with a similarity to short-period cometary nuclei, to some KBOs and Centaurs.

Photometric observations have seen a rapid improvement in the last few years. A wide range of broadband colors has been found in the Centaur and TNO populations. The colors vary from neutral or slightly blue for 2060 Chiron to very red for 5145 Pholus and 7066 Nessus (Barucci et al. 1999, T12-002, Doressoundiram et al. 2001, T12-016, Boehnhardt et al. 2001, T12-007, Jewitt and Luu, 2001, T12-020, and Hainaut and Delsanti, 2002, T12-019). Barucci et al. (2001, T12-004) analyzing the colors (B-V, V-R, V-I, and V-J) of TNOs and Centaurs and using the same statistics applied to define the current asteroid taxonomy, found a continuous spread of the objects between neutral color and very red. Pushing further the analysis, the TNOs may be split into four groups. This difference can be produced by some energetic processing (exposures to cosmic rays, solar ultraviolet, corona discharge, and/or ion bombardment) on surface ices, organic solids, and minerals.

Most of the information on the surface composition comes from studies in the near-infrared obtained with the largest telescopes (Keck and VLT). Only a few TNOs have been observed in the near-infrared and their surface characteristics show a wide diversity. 1996 TL_{66} as well as 2000 EB_{173} (Brown et al. 2000, T12-009, and Licandro et al. 2001, T12-023, Jewitt and Luu, 2001, T12-020) have flat featureless spectra similar to that of dirty water ice, while 1996 TO_{66} and 2001 PT_{13} show an inhomogeneous surface with the presence of small amounts of water ice mixed with other minor components (Brown et al. 2000, T12-009, Barucci et al., 2002, T12-006). In contrast, 1999 DE_9 shows solid-state absorption features near 1.4, 1.6, 2.00 and probably at 2.25 μm (Jewitt and Luu, 2001, T12-020).

Centaurs appear to have very similar spectral and color characteristics to the TNOs (Barucci et al., 2000, T12-003), thus supporting the hypothesis that Centaurs are ejected from the Kuiper belt by planetary scattering; this is the strongest observational argument for a common origin. Luu et al. (2000, T12-024) showed that the surface of 2060 Chiron contains water ice and discussed the implications of this for Centaurs and Kuiper belt objects. It is possible, perhaps likely, that also irregular satellites (high-inclination, elliptical orbits, retrograde or prograde) could be captured after extraction from the Kuiper Disk. Among these objects, Nereid (Neptune), Phoebe (Saturn) and Sycorax (Uranus) seem to have ice (Brown et al. 1999, T12-010, Brown 2000, T12-008, Owen et al. 1999, T12-026, Romon et al. 2001, T12-027).

4. Comets

4.1. Introduction

The very bright comets (C/1995 O1) Hale-Bopp and (C/1996 B2) Hyakutake still were major topics of cometary research. A second conference (IAU Colloquium 186 "Cometary Science after Hale-Bopp", Tenerife, January 2002) concentrating on Hale-Bopp attempted to summarize these efforts. The exceptional activity and the early detection of comet Hale-Bopp as well as the coincidence with the operational phase of the Infrared Space Telescope resulted in a major step forward in the detection and observation of chemical compounds.

The Deep Space 1 mission of NASA's New Millennium program passed comet 19P/Borrelly on 22 Sept. 2001 and provided images of a cometary nucleus for the second time 15 years after the comet Halley missions in 1986. The elongated 8 km long nucleus was covered with a resolution of about 100 m over an extended range of phase angles.

The Stardust mission (Discovery series) to comet 81P/Wild 2 is well on its way to collect a coma sample and to return it to Earth. The multiple comet fly-by mission Contour unfortunately failed shortly after launch in June 2002. A further NASA mission is Deep Impact that will drop a mass of 350 kg into the nucleus of comet 9P/Tempel 1 during a fly-by in July 2005. The ESA cornerstone mission Rosetta is on schedule to be launched in January 2003. It will rendezvous with comet 46P/Wirtanen for several years in late 2011 after passing the asteroids 140 Siwa and 4979 Otawara.

There has been strong support by the community for observations and modelling of target comets and asteroids in support of space missions.

4.2. Nucleus: Observations

Ground-based observations of comet nuclei are very difficult because inactive nuclei are faint objects. Interesting results were obtained using the Hubble Space Telescope for comets 22P/Kopff (Lamy et al., 2002), 9P/Tempel 1 (Lamy et al., 2001) and 45P/Honda-Mrkos-Pajdušáková (Lamy et al., 1999). Particular attention was given to comets that are the target of space missions, such as 2P/Encke and 19P/Borrelly (Fernandez et al., 2001; Sanzovo et al., 2001), or to extraordinary comets such as C/1996 B2 Hyakutake (Lisse et al., 1999). An extensive study of the nuclear magnitudes of Jupiter family comets is being

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conducted. The catalogue now comprises more than 100 comets (Tancredi et al., 2000; Licandro et al., 2000). A first results paper (Soderblom et al., 2002) of the encounter of the spacecraft Deep Space 1 with comet 19P/Borrelly revealed a very dark and elongated nucleus with low activity rather similar to the nucleus of comet Halley and in which variegation of surface regions could be seen.

4.3. Nucleus: Modeling

Theoretical nucleus modeling, used to link coma observations to physical nucleus properties, is now a mature field as can be seen from the good results obtained by the application of such models to well studied comets such as Halley and Hale-Bopp (Julian et al., 2000; Capria et al., 2000) and also to less observed comets such as 82P/Gehrels 3 (De Sanctis et al. 2000). In the last few years, papers dealing with the subject from a new point of view were published: Skorov et al., 2001; Shoshany et al., 2002; Moreno et al., 2002. For the planning of comet space missions, it is important to have at least an idea of the comet environment, and the theoretical simulation of comets can usefully integrate ground-based observations. Some of the authors concentrated on these comets, in particular on the target of the Rosetta mission, 46P/Wirtanen: Kossacki et al. (1999); Moehlmann (1999); Capria et al. (2001). A group of authors concentrated on the theoretical study of surface properties: Hughes (2000); Skorov and Rickman (1999a); Skorov et al. (1999b); Skorov et al. (2002); Davidsson and Skorov (2002). The effects of the irregular shape of nuclei were studied by Gutierrez et al. (2000); Gutierrez et al. (2001). It is interesting to note that F. Whipple, who posed the basis of nucleus modeling in 1950 with the "dirty snowball" theory, is still active and recently published a study on the magnitude variation of Kuiper Belt and Oort cloud comets (Whipple, 2000).

4.4. Cometary Gas Coma

A large number of papers have been published on the coma physics and chemistry in the last three years emphasizing theoretical models and/or new observations. Some radio and infrared observations have concentrated on the water molecule (Chiu et al., 2001; Mäkinen et al., 2001a,b; Neufeld et al., 2000; Graham et al., 2000; Dello Russo et al., 2000), on CO (Gunnarsson et al., 2002; DiSanti et al., 2001; Festou et al., 2001), on HCN (Woodney et al., 2002; Snyder et al., 2001; Mousis et al., 2000; Veal et al., 2000; Hirota et al., 1999), on ethane (Dello Russo et al., 2001), and other molecules (Mumma et al., 2001; Weaver et al., 1999a).

The morphology and the chemical processes in the coma have been treated in papers relating to models (Rodgers & Charnley, 2002; Vasundhara, 2002; Kerola & Larson, 1999) and to observations in the visible spectral range (Korsun & Jockers, 2002; Morgenthaler et al., 2001).

In the last few years several interesting observations of comets have been performed with high resolution spectrographs over the entire visible spectral range. Catalogs of emission lines in the visible spectral range have been obtained for two comets by Cochran and Cochran (2002) and Zhang et al. (2001). Analysis of molecular bands in the nuclear region have been done by Kawakita et al. (2001a, 2001b) and Glinski et al. (2001) on NH_2 and NH_3, Rousselot et al. (2001) on C_3 radicals, Wyckoff et al. (2000) determining carbon isotope abundance. Some high resolution analysis has been done even on the ion tail looking at ionized molecules, e.g., by Cochran et al. (2001) for N_2^+ and CO^+.

4.5. Dust Coma and Tail

During the last three years, the majority of the articles have focused on the interpretation of dust coma observations at visible and infrared wavelengths.

The analysis of the infrared spectra of comet Hale-Bopp by ISO and from the ground (Wooden et al., 1999) suggest the presence of both crystalline and amorphous silicates in the coma of comet Hale-Bopp.

There is much debate about a possible explanation because crystalline silicates are thought to form only at high temperature. Nuth et al. (2000) proposed a mechanism to produce crystalline grains by thermal annealing in the inner nebula and to transport them to the outer (cold) part, where comets formed. Bockelée-Morvan et al. (2002) propose that crystalline silicates could have been brought to the outer nebula by turbulent radial mixing. Their model also explain the D/H ratios measured in the solar system.

Another puzzling observation is that of sub-micron dust grains producing a large contribution to the cross-sectional area in the coma of comet Hale-Bopp, evidenced by spectrophotometric and polarimetric observations (Woodward et al., 2000; Mason et al. 2001; Vasundhara 2002).

In addition, tail inversion models are now applied to infrared continuum observations (Epifani et al., 2001). This is a continuation of routine work whose aim is to retrieve the slope of the dust size distribution in comets. New multi-color photometry has also been used to derive this parameter for comet Tabur (C/1996 Q1) by Kolokolova et al. (2001).

4.6. Split Comets

During the last few years, it has become clear that fragmentation and splitting in comets are much more common than was previously thought; many of the comets that recently passed through the inner Solar System experienced these phenomena. Splitting and fragmentation were addressed in the literature both from a theoretical point of view (Samarasinha, 2001) and a dynamical point of view (Sekanina et al., 2002; Desvoivres et al., 2000; Desvoivres and Klinger, 2002).

In theory, the splitting of comets can occur for several reasons. The nucleus can breakup when the spin period gets below a critical period which depends on the nucleus density and shape, and on the tensile strength of the cometary material. New calculations indicates that the angular momentum of a comet nucleus tends to increase with time (Neishtadt et al., 2002), thus confirming this idea. Davidsson (2001) derived new expressions for the critical period taking into account the strength of the cometary material, and showed that a low tensile strength (< 100 Pa) is compatible with the observational data. A second mechanism is the splitting due to tidal forces when the body gets within the Roche limit of a planet (or that of the Sun). Davidsson (1999, 2001) derived new expressions for the Roche limit for biaxial ellipsoids and showed that the tidal splitting distance is strongly dependent upon the nucleus shape. Thermal stresses have also been proposed as a source of disintegration (Tambotseva and Shestakova, 2001) from a numerical thermal model. Samarasinha (2001) developed this idea and proposed that the splitting of comet LINEAR (C/1999 S4) is due to the sublimation of "super-volatile" species in voids within cometesimals as a result of the propagation of the heating wave into the nucleus.

The breakup of comet LINEAR (C/1999 S4) in July 2000 offered a good opportunity to study the breakup mechanism and retrieve information on comet nuclei in general. The progenitor was a small comet nucleus with a radius ~ 0.5 km (Altenhoff et al., 2002; Farnham et al., 2001). A depletion in the volatile species CO and CH_3OH was observed before the splitting (Bockelée-Morvan et al., 2001; Weaver et al., 2001; Farnham et al., 2001), in contradiction with the idea that these volatile species played a significant role in the splitting (Weaver et al., 2001). According to measurements of the nucleus activity, the breakup must have occurred on July 23, but the main nucleus may have been losing debris for weeks before (Weaver et al., 2001; Bockelée-Morvan et al., 2001). A total of 16 fragments were observed through early August. The biggest fragments had typical sizes of 50-100 m and masses of about 10^8 kg (Weaver et al., 2001).

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4.7. Comet Hale-Bopp

Comet Hale-Bopp (C/1995 O1) has been one of the brightest comets of the twentieth century, and without any doubt the brightest since electronic detectors became available. It offered the opportunity to: (i) monitor its activity from perihelion through large heliocentric distances, (ii) monitor its dust and gas structures near perihelion, and (iii) perform high resolution spectroscopy. Although its perihelion passage took place five years ago, many exciting articles concerning this comet are still being published.

While the spin period is now established at 11.3 hours (Jorda et al., 1999; Licandro et al., 1999; Lisse et al., 1999; Pittichová et al., 1999), the direction of the spin axis is still subject to debate (Jorda et al., 1999; Licandro et al., 1999; Samarasinha et al., 1999). The interpretation of the dust features observed during a long period of time around perihelion does not seem to converge to a single pole orientation (Vasundhara and Chakraborty 1999; Farnham et al. 1999). Since a precession of the spin axis is excluded for theoretical reasons (Samarasinha 2000), the problem is likely to come from the interpretation of the dust/gas coma images.

Spectacular radio monitoring of the comet's activity covering a range of heliocentric distances of 1–7 AU (Biver et al., 1999; Colom et al., 1999) was performed. Additional spectroscopic observations by the HST (Weaver et al., 1999b) have allowed measurement of the water production rate in the UV at 2.5–4.4 AU post-perihelion. The main results are as follow: (i) the water production rate at perihelion is $\sim 10^{31}$ s^{-1}, (ii) the gas production rate decreases more rapidly post- than pre-perihelion, and (iii) the coma exhibits spatially asymmetric features. These data have been used to constrain the thermal conductivity, which is found to be relatively low (lunar-like) (Kührt, 1999). The H_2O and CO production rates are best fit by a model in which the nucleus is formed by amorphous water ice in which CO would be partially trapped (Enzian, 1999).

More than 20 molecules (neglecting ions and isotopes) have been detected in the coma of comet Hale-Bopp, mainly through emission lines at infrared and radio wavelengths. Several new species detected in comet Hale-Bopp are also observed in hot cores of star forming regions (Bockelée-Morvan et al., 2000). Altogether, these detections reinforce the link between cometary and ISM ices. Relative abundances of ethane and acetylene suggest Hale-Bopp's ices were altered by radiation and/or chemical reactions in the proto-solar nebula (Dello Russo et al., 2001).

4.8. Sungrazers

The Solar and Heliospheric Observatory (SOHO) is a cooperative mission between ESA and NASA devoted to study the Sun and its environment, but it has become very interesting also for cometary scientists because of the large number of comets discovered. The Large Angle Spectrometric Coronagraph (LASCO) discovered the 500th SOHO comet in August 2002, and most of the objects are sungrazing comets. It is possible to look at the real-time images and other information on the comets discovered on the web page http://sungrazer.nascom.nasa.gov/. Several amateurs discovered new sungrazing comets looking at the images just obtained and shown on this web page.

Some attempts have been done to study the characteristics of specific objects. Biesecker et al. (2002) reported the light curves for the 141 Kreutz comets discovered from 1996 through 1998 with LASCO. Their results show distinctive characteristics about the properties of the nuclei. Some properties can be derived from observation of the sungrazers in tight pairs that occasionally appeared in the field of view of LASCO (Sekanina, 2000a) or by applying a nucleus model (Iseli et al., 2002). The tails of some sungrazers have been analyzed (Uzzo et al., 2000) and for larger sample of comets (Sekanina, 2000b). First statistics on these objects have started to be published (Sekanina, 2002) considering the SOHO/LASCO observations and the ancient Chinese solar observations (Strom, 2002).

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