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COMMISSION 15 PHYSICAL STUDY OF COMETS AND MINOR PLANETS

ÉTUDE PHYSIQUE DES COMÈTES ET DES PETITES PLANÈTES

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COMMISSION 15 WORKING GROUPS

Div. III / Commission 15 WG	**Physical Study of Comets**
Div. III / Commission 15 WG	**Physical Study of Minor Planets**
Div. III / Commission 15 TG	**Comet Magnitudes**
Div. III / Commission 15 TG	**Asteroid Magnitudes**
Div. III / Commission 15 TG	**Asteroid Polarimetric Albedo Calibration**
Div. III / Commission 15 TG	**Geophysical and Geological Properties of Asteroids and Comet Nuclei**

TRIENNIAL REPORT 2006 - 2009

1. Introduction

The Commission 15 report was prepared primarily by the chairpersons of the two working groups: T. Yamamoto of the Comet Working Group and R. A. Gil-Hutton of the Minor Planet Working Group. In particular, the Comet section was produced by T. Yamamoto with the assistance of D. Bockelée-Morvan, H. Kawakita, and D. Prialnik, while the Minor Planet section was produced by R. A. Gil-Hutton with the assistance of A. Cellino, A. W. Harris (DLR), R. Jedicke, A.-C. Levasseur-Regourd, R. M. Schulz, T. B. Spahr, and P. Vernazza. W. F. Huebner was responsible for the Introduction. The final editing and merging of the various sections and subsections of the report was carried out by the Commission Secretary, D. C. Boice.

Scientific activity in the field has continued to grow in the past three years, as evidenced by the large number of publications in the refereed literature. The publication list cannot be accommodated in the space at our disposal. We have therefore chosen to highlight a representative subset of these publications to provide a snapshot of the current state of the field, and, as in the last several reports, without including a comprehensive bibliography. Instead, a complete list of the references used in creating this report, assembled by searching the ADS abstract service `<adsabs.harvard.edu/abstract_service.html>`)

to generate a list of refereed papers published between July 2005 and June 2008, inclusive, is available in the Archive section of the Division III *Physical Studies of Comets and Minor Planets* web site. This site can be reached (since it does not have a permanent home) via a link from the IAU home page.

Three task groups have been set up in Commission 15. A Task Group on *Asteroid Magnitudes* is co-led by E. F. Tedesco and R. A. Gil-Hutton, a Task Group on *Asteroid Polarimetric Albedo Calibration* is co-led by A. Cellino and R. A. Gil-Hutton, and a Task Group on *Comet Magnitudes* is co-led by G. Tancredi and T. Yamamoto. A fourth Task Group for *Geophysical and Geological Properties of Asteroids and Comet Nuclei* is being set up and co-led by K. Muinonen, R. A. Gil-Hutton and T. Yamamoto. While all task groups are of general scientific interest, they are also of great importance for the development of countermeasures against potentially hazardous objects as reported by W. F. Huebner and L. N. Johnson at the Tunguska conference in Moscow, 26-28 June, 2008.

2. Comets

Over 1100 peer-reviewed papers were published in the period of this triennial report from July 2005 through June 2008 (this number is based on a query to the Astrophysics Data System, ADS, at: `<adsabs.harvard.edu/abstract_service.html>`). It illustrates that comet science is actively pursued internationally by researchers active in the field.

2.1. *Comet nuclei*

The *Deep Impact* mission, during which a spacecraft collided with, and excavated the nucleus of Comet 9P/Tempel 1 on 4 July, 2005 (A'Hearn *et al.* 2005), was undoubtedly the major event and the main source of information on comet nuclei in the past three years. The impact showed the cometary nucleus to be very weak on scales ranging from the impactor diameter ($\sim$1 m) to the crater diameter ($\sim$100 m) and suggested that the strength might be low on much smaller scales as well. It also showed the cometary nucleus to be extremely porous (with a density of only 350 kg m^{-3}) and the ice to be close to the surface, but below a devolatilized layer. The ambient observations showed a huge range of topography, implying ubiquitous layering on many spatial scales, frequent (more than once a week) natural outbursts, many of them correlated with the spin phase, a nucleus surface with many features that are best interpreted as impact craters, and clear chemical heterogeneity in the outgassing from the nucleus. The mission prompted a large number of studies – observational, phenomenological, and theoretical – in the endeavor to interpret and understand the large body of accumulated data. The shape, topography, temperature distribution, spin state, composition, and activity pattern of the Tempel 1 nucleus were analyzed and discussed in a long series of papers published in *Icarus* in two dedicated volumes (Vol. 187, issue 1, March 2007, pp. 1–356, and Vol. 191, issue 2, October 2007, pp. 283–674).

Another well studied comet nucleus was 67P/Churyumov-Gerasimenko, the new target of the *Rosetta* mission. Its shape, size, spin, and density were derived by Lamy *et al.* (2007) from light-curve observations and non-gravitational force modeling.

A new catalog of nuclear magnitudes, size distribution, active area fractions, and production rates of Jupiter-family comets was compiled by Tancredi *et al.* (2006). Spin rates and colors of a number of Jupiter-family comets were obtained by Snodgrass *et al.* (2006) and compared with Kuiper Belt objects, from which these comets are believed to originate.

The origin and early evolution of comet nuclei was studies in a series of papers published in April 2008 in a dedicated volume of the Space Science Reviews. Comet 81P/Wild 2 nucleus samples returned to Earth by the *Stardust* spacecraft pointed to a wide range of formation conditions, probably reflecting very different formation locations in the protoplanetary disk (Zolensky *et al.* 2006). As a result of the recent close observations of comet nuclei (Borrelly, Wild 2, and Tempel 1), the old 'rubble-pile' comet nucleus model was revised and constrained (Basilevsky & Keller 2006) and a new model for the interiors of Jupiter family comet nuclei was proposed by Belton *et al.* (2007), called the 'talps' (or 'layered pile' model), in which the interior consists of a core overlain by a pile of randomly stacked layers, primordial remnants of the early agglomeration phase.

The major nucleus outburst event during this period was that of Comet 17P/Holmes in October 2007 (Sekanina 2007), an unusual outburst both in timing and in scale: the nucleus brightened by about 9 magnitudes, at a rate of 0.5 mag/hr, at a distance of 2.4 AU on the outbound leg of the orbit. The cause of the outburst is still unknown (Moreno *et al.* 2008), but outburst observations led to the determination of the chemical composition of the nucleus (Dello Russo *et al.* 2008 and references therein; Bockelée-Morvan *et al.* 2008). Outbursts and evidence of splitting were detected in 2006 for fragments of the nucleus of Comet 73P/Schwassmann-Wachmann 3, which had split into several pieces in 1995 (Tetsuharu 2007; Bonev *et al.* 2008; Ho *et al.* 2008). Mechanisms for cometary outbursts in general were discussed by Gronkowski (2005a, b; 2007a, b) in a series of papers, and by Sekanina (2007).

Modeling of comet nuclei focused on quasi 3-D calculations and numerical approaches to non-spherical shapes (Davidsson *et al.* 2005; Skorov *et al.* 2006; Ivanova & Shulman 2006; Kossacki *et al.* 2006, DeSanctis *et al.* 2007). In addition, the first fully 3-D comet nucleus model was developed (Rosenberg & Prialnik, 2007). The topic of heat and gas diffusion in comet nuclei was reviewed, discussed and analyzed in a monograph published by ESA for the International Space Science Institute (Huebner *et al.* 2006).

2.2. *Gas coma, chemistry, plasma, and tails*

The study of compositional diversity among comets motivated several observational campaigns. In 2005 - 2008, many studies focused on the long-period Comets C/2001 Q4 (NEAT), C02002 T7 (LINEAR), C/2004 Q2 (Machholz), and C/2006 P1 (McNaught), which made spectacular apparitions, and on the short-period Comets 73P/Schwassmann-Wachmann 3 (SW3) and 8P/Tuttle, which made a close approach to Earth, and on 17P/Holmes, which underwent a mega-outburst in October 2007. Observations of the gas coma of 9P/Tempel 1 were carried out in support to the *Deep Impact* mission and are reported in a special issue of Icarus (see above).

An important result is the remarkable similarity of composition of fragments B and C of Comet SW3, in contrast to the diversity of the overall comet population, and the peculiar chemistry of this comet showing strong depletions for many species (Dello Russo et al. 2007; Kobayashi *et al.* 2007; Villanueva *et al.* 2007; Lis et al. 2008). The peculiar compositions of Comets C/2001 A2 (LINEAR), 96P/Machholz, and 8P/Tuttle provide also new evidence for chemical diversity (Biver *et al.* 2006; Langland-Shula *et al.* 2007; Magee-Sauer *et al.* 2008; Bonev *et al.* 2008). Direct measurements of the NH_3 abundances have been obtained in several comets (Biver *et al.* 2007; Magee-Sauer *et al.* 2007).

New spectral emission lines were also detected in cometary spectra, e.g., rotationally resolved H_2 transitions originating from the highly excited rovibrational levels of the $X^1\Sigma_g^+$ state using *FUSE* (Liu *et al.* 2007). Detailed modeling of the $A^1\Pi$–$X^1\Sigma^+$ system of CO that includes opacity effects has been performed to analyze *HST* observations of several recent comets in the UV. No evidence for distributed sources of CO was found (Lupu *et al.* 2007). Spectroscopic observations of cometary gases provided information on physical coma parameters such as gas temperature, velocity, and distribution (e.g., Tseng *et al.* 2007; Bonev *et al.* 2007; Boissier *et al.* 2007).

Several isotopic measurements were obtained: $^{16}O/^{18}O$ in water (Biver *et al.* 2006b), $^{14}N/^{15}N$ and $^{12}C/^{13}C$ in CN and HCN. The $^{14}N/^{15}N$ ratio, observed now in a dozen comets, clusters around 140 (e.g. , Hutsemékers *et al.* 2005). A similar ^{15}N enrichment with respect to the Earth value ($^{14}N/^{15}N = 272$) has been measured in Comet 17P/Holmes, which is compatible with a production of CN from HCN (Bockelée-Morvan *et al.* 2008). This high enrichment is certainly indicative of fractionation processes that occurred in the solar or presolar nebula. Other constraints on the origin of cometary material may come from the accumulating measurements of the nuclear spin temperatures of H_2O, NH_3, CH_4 and CH_3OH (e.g. , Kawakita *et al.* 2006; Bonev *et al.* 2007; Pardanaud *et al.* 2007; Woodward *et al.* 2007).

Chemical modeling of cometary atmospheres remains the topic of several papers. A complex network involving C_2H_2, C_2H_6 and C_3H_4 is proposed to explain the spatial distribution of the C_2 and C_3 radicals in Comet Hale-Bopp (Helbert *et al.* 2005). The chemistry of C, H, N, O, and S compounds corresponding to ions of masses smaller than 40 amu in the inner coma of 1P/Halley is investigated in details by Haider & Bhardwaj (2005). Noteworthy are recent hydrodynamic simulations of the gas coma which show that gas structures produced by nucleus composition inhomogeneities and nucleus shape and topography are indistinguishable (Zakharov *et al.* 2008).

The first direct imaging of the interaction a comet (2P/Encke) with a coronal mass ejection was obtained with high temporal and spatial resolution with the SECCHI Heliospheric Imager-1 (HI-1) aboard the *STEREO* mission, and strongly supports the idea that large-scale tail disconnections are magnetic in origin (Vourlidas *et al.* 2007). Frequent disruptions in the plasma tails of Comets C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR), due to ubiquitous solar wind flow variations, were observed by the Earth-orbiting *Solar Mass Ejection Imager* (*SMEI*) (Buffington *et al.* 2008).

The encounter of the *Ulysses* spacecraft with the ion tail of Comet C/2006 P1 McNaught revealed the unexpected presence of magnetic turbulence and energetic ions at 1.6 AU from nucleus, and the presence of O^{3+} ions for the first time in a comet (Neugebauer *et al.* 2007). Observations of Comet McNaught with the Heliospheric Imager on *STEREO* support the presence of an iron tail in this comet (Fulle *et al.* 2007), in addition to a sodium tail (Leblanc *et al.* 2008). A number of MHD models have been developed to understand disconnection events and to analyze or prepare space investigations of solar wind interactions with cometary plasmas (e.g. Benna & Mahaffy 2006; Jia *et al.* 2007; 2008; Ekenbäck *et al.* 2008; Delamere 2006).

2.3. *Comet dust and distributed sources*

Our understanding of the complexity of cometary dust has been significantly progressing during the past triennium: The *Stardust* mission, brought for the first time dust samples from the coma of a comet (81P/Wild 2) and the *Deep Impact* mission released dust for remote observations from the subsurface of another comet (9P/Tempel 1). These missions have been complemented by ground observations, i.e., spectroscopic observations providing information about the composition of the dust and polarimetric observations providing information about the physical properties of the dust.

Numerous observations of Comet 9P/Tempel 1, in relation to the *Deep Impact* mission, have suggested the presence in the coma of low velocity, large, absorbing dust

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particles, which induced a high polarization and were probably covered by carbonaceous compounds (Farnham *et al.* 2007; Hadamcik *et al.* 2007). Immediately after impact, the polarization in the innermost coma decreased and a negative polarization color spectral gradient was noticed, most likely due to a drastic change in the composition of the dust ejected by the nucleus (Harrington *et al.* 2007). The event actually prompted the ejection of high speed, low albedo and high polarization dust particles from the surface, as well as of lower speed, higher albedo and slightly lower polarization particles coming from the subsurface (Sugita *et al.* 2005; Furusho *et al.* 2007). Observations near 11 μm gave clues to the presence of amorphous and crystalline olivine and pyroxene after impact (Harker *et al.* 2007).

Analyses of the samples from the *Stardust* mission have shown the presence of a very wide range of olivine and low Ca-pyroxene compositions, possibly reflecting various formation regions in the protoplanetary nebula, and of refractory organic compounds (Zolensky *et al.* 2006; Flynn, 2008). Observations of the craters on aluminum foils and tracks in aerogel indicate that both aggregates of submicrometer grains and compact particles with sizes up to a few tens of microns were present in the coma of the comet (Hörz *et al.* 2006; Burchell *et al.* 2007).

Such a structure was previously suggested from numerical and laboratory simulations of the polarimetric observations of Comet C/1995 O1 Hale-Bopp and other high-polarization comets. An excellent match was found for samples, of tens to hundreds of micrometer sized, fragile, fluffy particles corresponding to mixtures of silica-rich, magnesio-silica and ferrosilica with fluffy carbon, for an average grain size in the 0.1 μm size-range or with a few large compact grains added (Lasue & Levasseur-Regourd 2006; Hadamcik *et al.* 2007). Also, the ensemble of results obtained for interplanetary dust indicate that its light scattering and thermal properties stem from the presence of compact and fluffy particles, with compositions ranging from silicates to more absorbing materials, with a decreasing contribution of the latter with decreasing solar distance (Levasseur-Regourd *et al.* 2007).

Another important event, as far as light scattering by cometary dust is concerned, was related to polarimetric observations of the fragments of Comet 73P/Schwasmann-Wachmann 3. A high polarization, indicative of continuous fragmentation of dust particles was pointed out, together with a lower polarization in the vicinity of fragment B, with a possible inversion of the spectral dependence of the polarization (Hadamcik & Levasseur-Regourd 2007; Jones *et al.* 2008; Bonev *et al.* 2008). Infrared observations from the *Spitzer* telescope revealed silicate emission features similar to those usually noticed in the comae of active comets (Sitko *et al.* 2006).

2.4. *Cometary materials origins and laboratory experiments*

Huebner (2008) reviewed the origin of cometary materials based on recent observations and theoretical studies. Measurements of the isotopic ratios and the nuclear spin temperatures in molecules are important to investigate origin of cometary materials (see section on Gas coma, chemistry, plasma, and tails). Horner *et al.* (2007) discussed constraints on the formation region of comets from their D/H ratios. Relating to the origin of cometary materials, mechanisms of the outward transport of materials in the solar nebula are investigated theoretically by, e.g., Boss (2007, 2008), Ciesla (2007), and Mousis *et al.* (2007). Such outward transport is necessary to explain co-existence of icy materials with high-temperature processed materials like crystalline silicates and CAIs in cometary grains (see Section Comet dust and distributed sources).

Many laboratory studies were carried out. Bar-Nun *et al.* (2007a; 2007b) measured the efficiency of gas (CO, Ar, and N_2) trapping into amorphous water ice and physical properties of cometary ice analogues at low temperatures.

Measurements of transition frequencies (or wavelengths) as well as transition strengths are also important to investigate molecules in cometary comae. The pure rotational spectrum of anti-ethylamine ($CH_3CH_2NH_2$) from 10 to 270 GHz was studied in the laboratory by Apponi *et al.* (2008). Vander *et al.* (2007) reported a new set of line parameters for the transitions of C_2H_6 at 12 μm.

Photodesorption from ices of astrophysical relevance (Thrower *et al.* 2008) and desorption energies of H_2O, CH_3OH, and NH_3 for pure ices of these molecules (Brown & Bolina, 2007) were also investigated experimentally. Furthermore, many experimental studies were performed on interstellar or cometary ice analogues (made from simple molecules such as H_2O, CO_2, and CO) irradiated by high-energy particles like UV-photons, electrons, and ions. Complex molecules could be formed in these ices at low temperatures (e.g. , Baratta *et al.* 2008; Bennett & Kaiser 2007; Bennett *et al.* 2006, 2007; Brucato *et al.* 2005, 2006), while simple molecules or atoms were desorbed from the icy surfaces in some cases (e.g., Zheng *et al.* 2006; Bennett & Kaiser 2005). Charge exchange cross sections for highly ionized C, O, and Ne on H_2O, CO, and CO_2 were measured to investigate X-ray emission lines from comets by Mawhorter *et al.* (2007).

3. Asteroids, Trojans, and Centaurs

Sometimes, many detailed considerations may be nicely summarized by one simple number. In the case of this report, this number is 808. This is the number of peer-reviewed papers published between June 2005 and June 2008, having as subject the asteroids (resulting from a query to the Astrophysics Data System, ADS, at the address <adsabs.harvard.edu/abstract_service.html>). This number clearly demonstrates that asteroid science is experiencing a phase of active development, and the number of scientific articles produced by many teams active in the field is constantly increasing. On the other hand, this also means that it is simply impossible to produce an exhaustive list of relevant papers to be explicitly quoted in this document. For this reason, this section is mostly focused on very general facts and achievements.

The past triennium has seen one major accomplishment, namely the rendezvous of the Japanese space probe *Hayabusa* with the near-Earth asteroid (25143) Itokawa, and the subsequent experiment aimed at collecting a sample of material from the body's surface, to be sent back to Earth. While the latter part of the mission is still in progress, the detailed *in situ* exploration of this tiny object has produced many important results in terms of surface texture, regolith properties, and likely overall structure of this object.

The availability of increasingly larger telescopes and improved detectors has made possible important developments in the studies of the most distant asteroidal bodies, including Jupiter Trojans and Centaurs. In particular, important spectroscopic campaigns have been carried out by different teams. Other exciting results have been produced by high-resolution imaging techniques, which have led to the discovery of many new binary systems among asteroids and Trans-Neptunian objects, including the discoveries of the triple systems whose primary components are (45) Eugenia and (87) Sylvia.

In addition to the above topics, very important results have been obtained in a variety of studies dealing with physical and dynamical properties of the asteroid population. They will be mentioned in the following subsections.

3.1. *Photometry, shapes, and spin properties*

The last triennium has seen the developments of important techniques of inversion of lightcurves, as well as of sparse photometric data. These techniques will be extremely important in the forthcoming years, when next-generation sky surveys like PAN-Starrs and *Gaia* will start to produce huge amounts of data. In addition, the Yarkovsky - O'Keefe - Radzievskii - Paddack (YORP) effect has been widely investigated. This is a thermal radiation torque that can sensibly alter the spin state of small asteroids, and indirectly affect also the rate of the Yarkovsky-driven drift in semi-axis, with important consequences for the supply of near-Earth objects.

3.2. *RADAR, thermal IR, optical polarimetry, and light-scattering phenomena*

The period of this report has seen the publication of a large number of studies using thermal-infrared (IR) techniques to derive the sizes and albedos of various types of minor planets, including four asteroids and inactive comets (Kraemer *et al.* 2005); 25 asteroids in comet-like orbits (Fernandez *et al.* 2005); three Jupiter Trojans (Emery *et al.* 2006); the potential spacecraft target (10302) 1989 ML (Müller *et al.* 2007); 42 Centaurs and KBOs from *Spitzer Space Telescope data* reviewed by Stansberry *et al.* (2008); three Mars Trojans (Trilling *et al.*; 2007), four near-Earth asteroids (Wolters *et al.* 2008); and the Rosetta fly-by target (21) Lutetia (Müller *et al.* 2006; Carvano *et al.* 2008). A review of *Spitzer Space Telescope* observations of small bodies was given by Fernandez (2006).

The surface properties of small asteroids from thermal-IR observations were reviewed by Harris (2006). Comparison of thermal IR results with those from radar provides a valuable control on the accuracy and applicability of these techniques in different circumstances, and greater insight into the physical properties of the target objects. Objects studied in detail by means of both radar and thermal-infrared observations include the *Hayabusa* mission target (25143) Itokawa (Ostro *et al.* 2005; Müller *et al.* 2005); (1980) Betulia (Harris *et al.* 2005; Magri *et al.* 2007); binary NEO 2002 CE26 (Shepard *et al.* 2006); (33342) 1998 WT24 (Harris *et al.* 2007; Busch *et al.* 2008); and (2100) Ra-Shalom (Shepard *et al.* 2008), for which sizes, albedos, and information on surface properties were obtained.

Surface thermal inertia and conductivity are important parameters that provide information on the nature of regolith and govern the magnitude of the Yarkovsky and YORP effects. Delbo' *et al.* (2007) carried out detailed thermophysical modeling to derive the first representative value for the thermal inertia of NEOs of 200 ± 40 $\mathrm{Jm^{-2}s^{-0.5}K^{-1}}$. A larger value of 750 $\mathrm{Jm^{-2}s^{-0.5}K^{-1}}$ was reported for (25143) Itokawa by Müller *et al.* (2007), who discuss the radar and thermal IR results for Itokawa in the light of the ground-truth data from the *Hayabusa* mission.

Polarimetry is also useful for asteroidal studies, since it provides information on physical parameters such as albedo and regolith porosity. A few objects exhibiting fairly exotic polarimetric properties have been pointed out (e.g., Barbara *et al.* 2006). Surface properties of Centaurs and Kuiper Belt objects have been tentatively estimated from near back scattering photometry and polarimetry, as reviewed in Belskaya *et al.* (2008).

3.3. *Spectra, taxonomy, composition, and space weathering*

Spectroscopic observations of asteroid families have been carried out in the visible and the NIR wavelength range, measurements in the latter being a premiere in this 'family-fiel. Vernazza *et al.*'(2006a) observed members of the 5.8 Myrs old Karin family and found (*i*) little spectral variation, thus suggesting a relatively homogeneous parent body; and (*ii*) a low degree of spatial alteration for the observed surfaces in agreement with the

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young age of the family. Moreover, the largest member of the family, 832 Karin, was found to be homogeneous throughout its rotation (Chapman *et al.* 2007; Vernazza *et al.* 2007). In the same young family register, Willman *et al.* (2008) found that the 1 to 5 Myrs old S/K-type Iannini family members have spectral slopes compatible with those of the Karin family. Mothé-Diniz *et al.* (2008) obtained NIR spectra for 30 members of the Eos family and found a spectral diversity that may suggest a slightly differentiated parent body.

Interesting is the discovery of V-type asteroids in the middle main belt (Roig *et al.* 2008). They predict that some middle main belt V-types may originate from Vesta (up to 30%) but that most of them must have a different origin. Sunshine *et al.* (2008) discovered CAI-rich bodies (their CAIs abundance being 2-3 times that of any meteorite); they suggest that these bodies are more ancient than any known meteorite. On the basis of four S-type spectra, Hardersen *et al.* (2006) suggest that these objects experienced partial melting temperatures during their formation. Spectroscopic studies in the NIR have also looked at the spectral properties of X- and M-type asteroids (Birlan *et al.* 2007; Ockert-Bell *et al.* 2008). Sunshine *et al.* (2007) compared the spectral properties of olivine-rich asteroids and meteorites. Interesting for the Dawn mission are the following two reports: (*i*) Rivkin *et al.* (2006a) report the absence (at a 1% level) of a 3 μm water band on Vesta throughout its rotation; and (*ii*) Rivkin *et al.* (2006b) suggest the presence of carbonates and iron-rich clays on Ceres' surface. New mid-IR asteroid spectra by Lim *et al.* (2005) have shown that a SNR higher than 50-100 is necessary for unambiguously detecting emission features. Emery *et al.* (2006) performed mid-IR spectroscopy of three Trojans with the *Spitzer* telescope and suggest the presence of fine-grained silicates on their surfaces.

Space weathering (SW) processes have been intensively studied over the past three years. Laboratory experiments have simulated both solar wind implantation and dust bombardment on silicate-rich materials. It has been shown that both processes tend to redden and darken the reflectance spectra of (*i*) silicates such olivine, ortho- and clino-pyroxene (Brunetto & Strazzulla 2005; Marchi *et al.* 2005; Brunetto *et al.* 2006a; Loeffler *et al.* 2008); and (*ii*) meteorites such as OCs and HEDs (Strazzulla *et al.* 2005; Vernazza *et al.* 2006b). Recent *in-situ* measurements performed on the S-type NEA (25143) Itokawa validated these experiments (Saito *et al.* 2006; Abe *et al.* 2006; Hiroi *et al.* 2006; Ishiguro *et al.* 2007): Hiroi *et al.* (2006) found that a dark region on the small (550 meter) asteroid (25143) Itokawa is significantly more space-weathered (spectrally redder) than a nearby bright region.

Brunetto *et al.* (2006b) created a space weathering model that reproduces the spectral reddening originating form ion irradiation. This model enables the use of scattering laws (Hapke & Shkuratov models) for the interpretation of remote sensing data.

Vernazza *et al.* (2006b) exposed a eucrite meteorite, thought to originate from Vesta, to ions in the laboratory to show that its parent should indeed be substantially more weathered than it appears. They suggest that Vesta must have a magnetic field of at least 0.2 microtesla at its surface, a few hundred times smaller than Earth's field, which diverts the damaging ions.

Finally, and in relation to space weathering effects, (*i*) a general spectral slope-exposure relation for S-type main melt and near-Earth asteroids has been established (Marchi *et al.* 2006a, b); and (*ii*) a general SW model has been proposed (Lazzarin *et al.* 2006; Paolicchi *et al.* 2007).

3.4. *Space missions*

Two space mission events highlighted this triennium, the *Deep Impact* mission to Comet 9P/Tempel 1 and the first coma dust sample return from Comet 81P/Wild 2 by the Stardust mission (the comet encounter occurred in 2004). The two missions resulted in a large number of publications, which were combined, for the most part, into special issues preceded by overview and introductory papers. For *Deep Impact* see: A'Hearn *et al.* (2005), A'Hearn & Combi (2007a, b, c), and A'Hearn (2008). For *Stardust* see Brownlee *et al.* (2006).

To enhance the scientific return of the *Deep Space 1* mission a coma model of Comet 19P/Borrelly during encounter was developed (Boice & Wegmann 2007). The first comprehensive description of the *Rosetta* mission to Comet 67P/Churyumov-Gerasimenko was provided in a special issue (see Glassmeier *et al.* 2007, for the mission summary paper).

Photometric and polarimetric observations were obtained in support of the Hayabusa mission to asteroid (25143) Itokawa (Cellino *et al.*, 2005; Thomas-Osip *et al.*, 2008). Several studies were published about what advances in asteroid science should be expected from the Gaia mission; see Mignard *et al.* (2007), Mouret *et al.* (2007) and Cellino *et al.* (2007) for the latest overviews. Regular updates of the status of the Dawn mission were published by Russell *et al.* (2006, 2007a, b).

3.5. *Near Earth Objects (NEO)*

In the time period covered by this triennial report 2010 new NEO discoveries were reported to the Minor Planet Center. Of these objects 176 are larger than 1 km in diameter (assuming a reasonable albedo) and 255 are Potentially Hazardous Objects (PHO). PHOs have a maximum close approach to the Earth's orbit (not necessarily the Earth itself) of 0.05 AU and therefore pose a larger impact risk to the Earth than the remainder of the NEO population. The Catalina Sky Survey telescopes now dominate the discovery statistics reporting about 2/3 of all new objects.

In response to the 2005 George E. Brown *Near-Earth Object Survey Act*, NASA convened a study team to assess the Earth impact risk and capabilities of future Earth and space-based NEO surveys. The objectives of the act are a new survey to detect, track, catalogue, and characterize 90% of NEOs that are larger than 140 m in diameter in 15 years. The NASA report (White Paper to the US Congress) is available at `<www.nasa.gov/pdf/171331main_NEO_report_march07.pdf>`.

The relatively recent idea that asteroids may have internal structures more like rubble piles than solid rock was spectacularly demonstrated by images from the Japanese *Hayabusa* spacecraft of asteroid (25143) Itokawa. The 2 June 2006 issue of Science highlighted the mission's results.

Other notable results include: The first laser guide star adaptive optics imaging of an NEO (Bush *et al.* 2007), the first direct detection of asteroid spin-up rates due to the YORP effect (Lowry *et al.* 2007), and the ongoing discovery of multiple NEO systems and unusual NEO shapes using radar imaging techniques (e.g., Ostro 2006). A report about PHO countermeasures was presented by Huebner *et al.* at the Tunguska conference in Moscow, June 2008.

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president of the Commission

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