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DIVISION III PLANETARY SYSTEMS SCIENCES

SCIENCES DES SYSTEMES PLANETAIRES

Division III provides a focus for astronomers studying a wide range of problems related to planetary systems, including the physical studies of planets, their satellites, small bodies (comets, asteroids and meteors), and including astrobiology and extrasolar planetary systems.)

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DIVISION III COMMISSIONS

Commission 15	Physical Studies of Comets and Minor Planets
Commission 16	Physical Study of Planets and Satellites
Commission 20	Positions and Motions of Minor Planets, Comets and Satellites
Commission 22	Meteors, Meteorites and Interplaentary Dust
Commission 51	Biostronomy
Commission 53	Extrasolar Planets

DIVISION III WORKING GROUPS

Division III WG	Near Earth Objects
Division III WG	Small Bodies Nomenclature (CSBN)
Division III WG	Planetary System Nomenclature (WGPSN)

INTER-DIVISION WORKING GROUPS

Division I-III WG	Natural Satellites
Division I-III WG	Cartographic Coordinates and Rotational Elements of Planets and Satellites

TRIENNIAL REPORT 2009–2012

1. Introduction

Division III, with 1126 members, is the third largest of the 12 IAU Divisions, focusing on subject matter related to the physical study of interplanetary dust, comets, minor planets, satellites, planets, planetary systems and astrobiology. Within the Division are very active working groups that are responsible for planetary system and small body nomenclature, as well as a newly created working group on Near Earth Objects which was established order to investigate the requirements for international ground-and/or space-based NEO surveys to characterize 90% of all NEOs with diameters >40m in order to establish a permanent international NEO Early Warning System.

2. Developments within the past triennium

2.1. *Commission 15 – Physical Studies of Comets and Minor Planets*

Commission 15 has 2 working groups: Physical Studies of Asteroids, Physical Studies of Comets, and 4 task groups on Asteroid magnitudes, Cometary Magnitudes, Asteroid polarimetric Albedo Calibration, and on Geophysical and Geological Properties of Asteroids and Comet Nuclei. The material for Commission 15 has been prepared by Alberto Cellino.

During the last triennium there has been an effort to completely re-design the Commissin web page. This has been done by Mrs. S. Rasetti at the Observatory of Torino, in collaboration with the Commission President and Secretary. The new web page can be found at URL http://iaucomm15.oato.inaf.it/. This web page includes a link to a brand new Forum, which has been developed with the aim of possibly becoming a useful tool for Commission 15 members. The idea is that, by registering in the Forum, each member will have the possibility to write text containing a variety of useful information, and will be automatically informed whenever a new message is posted. In this way, it should be possible to create a kind of dedicated network to facilitate interactions between Commission 15 members, to encourage the exchange of ideas, the sharing of telescope time, and meeting organization. This Forum has been very recently improved in order to add some important facilities, and might hopefully become a tool appreciated by the community.

During the last triennium, Commission 15 devoted particular attention, through the activities of two dedicated Task Groups, to the subjects of obtaining a new, updated calibration of the relation between geometric albedo and some polarimetric properties, and the need of assessing and possibly improving the quality and accuracy of asteroid absolute magnitudes. The fundamental role played by the absolute magnitude in numerous areas of research is well known. Thus, the generally poor accuracy of the H values listed in major databases certainly constitutes a problem, with potential consequences on the results of a number of investigations concerning the size frequency distribution of the population, and inferences on the most likely values of asteroid collisional impact strengths. This topics are sufficiently important to be separately discussed below.

Activities of the Task Group on Asteroid Magnitudes — The Task Group on Asteroid Magnitudes (TGAM) was charged with investigating the quality of asteroid absolute magnitudes and the accuracy of the asteroid magnitude phase function and to suggest ways to improve both. Absolute magnitudes are important for deriving accurate sizes and albedos. Upcoming projects will produce high accuracy photometry on well over 100,000 asteroids. An accurate asteroid magnitude phase function is needed to reduce these observations.

Different possible options to improve the definitions of albedo and absolute magnitude were discussed. There has been some debate among the task group members concerning the problems related to the "zero phase angle problem" when dealing with physical parameters that are defined at zero phase angle (such as H and albedo). The prevailing opinion was that it is probably premature to propose drastic changes in definitions of H or albedo because this could introduce many problems. For instance, a definition of absolute magnitude as the brightness observed at unit distance from the Sun and the observer, and at a phase angle of, say, 10 degrees, would work for asteroids, but not for other, more distant solar system objects which are visible only at smaller values of phase angle. Similar considerations may apply to the definition of geomtric albedo. However, there was consensus that some limited improvement in the definition of the (H,G) system, for instance, are not only possible, but sorely needed. Typical accuracies of H value in available catalogues is about ± 0.5 mag due to: (1) the often low signal to noise ratio of the measurements performed by the discovery surveys, (2) the crude photometric data reduction procedures employed by most current asteroid survey programs, which use unfiltered CCDs and do not use standard stars from photometric catalogs to calibrate the photometry, and (3) the ambiguity introduced by lightcurve effects.

In addition to these large random errors in H there are systematic errors as well. These have been noted previously (*e.g.*, Sec. 3.2.1 of Jurić *et al.* 2002 for a discussion of this particular issue, and Jedicke *et al.* 2002 for a broader treatment of issues regarding asteroid orbital element databases).

A possible way to improve the situation, in order to be ready to process properly the huge amount of new data which are going to be produced by present and imminent sky surveys, has been discussed in a paper by Muinonen *et al.* (2010). These authors have proposed the adoption of a new three-parameter photometric system (named H, G_1, G_2), which seems to produce better fits of the limited number of presently available high-quality phase-magnitudes curves, with respect to the currently adopted (H, G) system. The proposed system seems also potentially able to produce more accurate estimates of the absolute magnitude even in the vast majority of cases, when the sampling of the phase-magnitude curves is rather poor.

Activities of the Task Group on Asteroid Polarimetric Albedo Calibration — Polarimetry is an excellent technique to derive asteroid albedos, including small objects, and was used in the past also in asteroid taxonomy to distinguish between E, M, P classes, The empirical relations among the albedo and polarimetry parameters are therefore very important.

On the other hand, polarimetry has important advantages over thermal radiometry, the most used technique for size and albedo determination. Radiometric results are model-dependent, require observations in different IR bands, and generally suffer from poor knowledge of the absolute magnitude H. Radiometric albedos for small asteroids which are observed in only one IR band have uncertainties which may very high, up to 60%. In the past, different authors have used albedo-polarimetry relations obtained by several methods. Therefore IAU Commission 15 has recommended that astronomers converge to a unique choice of the albedo-polarimetric parameter empirical relations.

There is a general consensus that the well-known polarimetric slope-albedo relation must be urgently recalibrated using only high-quality V-band polarimetry of asteroids with accurate albedos. The best object list at present is the one by Shevchenko & Tedesco (2006), consisting of albedos derived from occultation and in-situ (four objects) size measurements, coupled with accurate estimates of absolute magnitudes obtained using one unique photometric system (H,G). Albedos determined using model-dependent fits to thermal spectra, and all results based on IRAS or single-wavelength radiometric observations, are not suitable for use as calibration objects, and should be no longer used for these purposes. Only albedos derived by using diameters from radiometric spectra fit using detailed thermophysical models can still be acceptable for calibration.

A reasonable road-map for the future is to obtain new data for albedo calibrations aimed at obtaining very accurate polarization measurements of the Shevchenko and

Tedesco target list. Some dedicated observing programs are presently ongoing and are starting to produce data which are expected to lead to a new, better caliobration of the polarization-albedo relation in the near future. On the other hand, some theoretical work is needed to explain the peculiar objects found during the last surveys (the so-called Barbarians, F-class, etc.).

Activites of the Task Group for Physical Properties of Near-Earth Objects — Since the IAU General Assembly in Rio de Janeiro, the Task Group for Physical Properties of Near-Earth Objects (TGNEO) has been involved in introducing a new three-parameter H, G_1, G_2 photometric function for asteroids (Muinonen *et al.* 2010), already mentioned in the previous Section 2.1. This was then followed by an application to photometric data available at the Minor Planet Center and carefully calibrated at Lowell Observatory (Oszkiewicz *et al.* 2011).

The three-parameter photometric phase function has been introduced as an improvement to the H, G photometric function approved at the IAU General Assembly in 1985. For the NEO cause, the H, G_1, G_2 photometric function allows for more accurate prediction of absolute magnitudes H based on sparse photometric data. Indirectly, this allows for more accurate size, geometric-albedo and Bond-albedo estimates to be derived.

The application of the new phase function has resulted in improved absolute magnitudes for over 500,000 asteroids, including more than 6,000 NEOs. Work is currently under way to correlate the individual G_1 and G_2 parameters with the individual geometric albedos, allowing for more accurate characterization of NEO sizes in particular.

2.2. *Commission 16 – Physical Study of Planets and Satellites*

Commission 16 had a face to face meeting of seven members during the American Astronomical Society's Division for Planetary Sciences conference in Pasadena, California in October 2010. At this meeting plans were made to update the Commission 16 web site for easier access to historical archives and ongoing Commission activities. Plans were also made to hold a Town Hall meeting to encourage new membership at the joint European Planetary Science and Division for Planetary Science Conference in October 2011 in Nantes, France. The Commission helped devel-op and sponsor several proposals for Symposia and Joint Discussions for the 2012 General Assembly in 2012.

2.3. *Commission 22 – Meteors, Meteorites and Interplanetary Dust*

After the GA in 2009, the president of Commission 22, J. Watanabe, started a Newsletter to inform members about commission business activities in a timely manner via e-mail. Since the first one was issued on Sept. 24, 2009, eleven newsletters have been released as of October 29, 2011.

New members were assigned to the Working Group on Meteor Shower Nomenclature, which is a new WG, changed from a task group at the last GA. New members have also been assigned to the WG on Professional-Amateur Cooperation in Meteors. All the members have been announced in the newsletter on the commission web site at http://www.iau-c22.org/.

The Meteoroids 2010 meeting was successfully held on May 24-28, 2010 in Colorado U.S.A. The business meeting of the organizing committee was held during this meeting. The next meeting will be held in Pozan, Poland in 2013. Detailed information will be released on the web: http://www.astro.amu.edu.pl/Meteoroids2013/. Commission 22 also proposed a joint discussion entitled "From Meteors and Meteorites to their Parent Bodies: Current status and future developments" at the next general assembly, 2012, in Beijing. This proposal has been approved as JD5.

2.4. *Commission 21 – Light of the Night Sky*

Since the last triennial report, and after extensive consultation with active members of Commission 21, it was decided to dissolve the Commission as it existed within Division III, and to reform it under the name of "Galactic and Extragalactic Background Radiation" under Commission IX.

2.5. *Working Group on Small Bodies Nomenclature*

The CSBN chaired by Jana Ticha continues its work and carries out its usual duties: collecting, judging, and approval of name proposals for minor planets as well as naming of comets. The CSBN still works in the close connection to the Minor Planet Center (both minor planets and comets) and the CBAT (comet names). Since the previous IAU triennium report (2008 July to 2011 October) 2140 minor planets, 6 satellites of minor planets and 546 comets were named. The total number of named minor planets is 16714 as of Oct. 12, 2011. Several batches of new names were the LINEAR discovery namings honor science students who are finalists in a series of science competitions and their teachers.

One of the CSBN goals is to consider names for various unusual objects such as NEOs, TNOs, minor planet satellites, binary bodies, targets of space missions, targets of detailed physical studies and other frequently cited objects. For the 2009-2012 triennium the most significant new names were for the TNO satellites (50000) Quaoar I = Weywot, (90482) Orcus I = Vanth, (120347) Salacia I = Actaea, main belt minor planet moons S/(216) 1 Alexhelios, S/(216) 2 Cleoselene and (702) Alauda I = Pichiüñëm.

In November 2010 the long-time Secretary of the WG SBN Brian G. Marsden unfortunately died. This was a very great loss to the small solar system body nomenclature work, of a wealth of his excellent knowledge, experience and insight. Gareth V. Williams began to serve as the new Secretary of the CSBN.

The CSBN also has been working to refine its naming guidelines for minor planets and satellites of minor planets and binary components of minor planets. Several members worked on the preparation of the web-based system for minor planet name proposals. The CSBN voting now all goes through the website, again in close cooperation with the MPC. The work of the WG will become much more efficient in the near future.

2.6. *Working Group for Planetary System Nomenclature*

From 1 September 2009 to 30 September 2011, 284 new names were assigned for planetary surface features (Mercury: 11, Venus: 14, the Moon: 3, Mars: 36, Phobos: 4, Dione: 16, Enceladus: 27, Rhea: 95, Titan: 26, Lutetia: 37, Vesta: 15). In addition the Jovian satellite Herse (Jupiter L) was named.

During this same time period the following additional actions have been taken:

- For Titan: Introduced the descriptor terms labyrinthus, lacuna and mons and their themes and amended the definition of the descriptor term lacus
- For the Moon: Updated the themes
- For Venus: Changed Metis Regio to Metis Mons, Ningal Undae to Ningal Lineae, Szl-anya Dorsa to Szl-anya Lineae, Tezan Dorsa to Tezan Lineae, and dropped: Mnemosyne Regio, Lab Patera, and Lorelei. Added Alexandra to the origin information for Danilova crater.
- For Mars: Expanded the theme for large craters and clarified the theme for small craters. Changed Oenotria Scopulus to Oenotria Scopuli.
- For Mimas: Changed Tintagil Chasma to Tintagil Catena
- For Rhea: Changed Kun Lun Chasma to Kunlun Linea and Pu Chou Chasma to Puchou Catenae
- For Itokawa: Approved the theme
- For Lutetia: Approved naming theme for features

- For Vesta: Set the themes and pre-approved a list of names
- For Mercury: Approved names for 6 map quadrangles.

3. Division Science

3.1. *Commission 15 – Physical Studies of Comets and Minor Planets*

IAU Commission 15 is living in an epoch of frantic activities and exciting discoveries, for reasons which are in part related to the results of important space missions. Currently, two such missions, Rosetta and DAWN, are flying, while another one, Hayabusa, has just recently terminated its tasks, bringing back to Earth some samples of matter taken from the surface of asteroid (25143) Itokawa, and two additional misisons, EPOXI and StardustNExT have just completed their encounter science. Apart from space missions, however, physical studies of asteroids and comets are producing a large harvest of important results, based on purely theoretical studies and on data collected by means of remote observations.

As in the past, the triennial report of Commission 15 has included two main sections corresponding to the reports written by the Chairs of the two biggest Working Groups of this Commission: the Ricardo Gil-Hutton for the WG on Physical Studies of Asteroids (previously known as WG on Physical Studies of Minor Planets, a nomenclature which is now obsolete), and Dan Boice for the WG on Physical studies of Comets. In addition, important input came from a number of colleagues active in a number of Task Groups, including Dominique Bockelée-Morvan, Walter Huebner, Karri Muinonen, Gonzalo Tancredi, who also helped to produce the two main WG reports. A complete list of the members of the WGs of Commission 15 can be found in the web page http://www.iau.org/science/scientific_bodies/commissions/15/.

It must be noted that the number of publications issued in the last triennium in the fields of relevance for Commission 15 is simply too large (about 1,000 papers) to allow us to make an exhaustive review, and for this reason this document does not include a bibliography. This means that the few articles quoted in the rest of this document, which have been taken from the original WG reports, represent only a tiny sample, and are certainly not aimed at representing "the" most important papers published in the triennium. The full references noted in the report may be found from the ADS website (http://adsabs.harvard.edu/abstract_service.html). This will give readers a chance to appreciate the very intense activity in this field, and the outstanding quality of a very large fraction of these studies.

The very intense scientific activity carried out by Commission 15 members and more in general by the whole scientific community active in this field is summarized below. Following a long tradition, this summary is made separately for Comets and Asteroids, but we should take into account that the separation between these two categories of minor bodies has become increasingly less sharp as new discoveries are being done. The recent discovery of the so-called main-belt comets, for example, clearly suggests that our traditional categories do not reflect the complex interrelations between minor bodies orbiting at different heliocentric distances.

Comet Nuclei — Recent spacecraft flybys of comets continue to dramatically improve our understanding of the physical properties of cometary nuclei, particularly the results from Deep Impact (and its extended mission, EPOXI) and Stardust (and its extended mission Stardust-NExT). The extended missions, EPOXI encounter of comet 103P/Hartley 2 and Stardust-NExT return to comet 9P/Tempel 1, were undoubtedly the major events in the past three years concerning comet nuclei. EPOXI flew past comet 103P/Hartley 2, an unusually small but very active nucleus, on 4 November 2010, obtaining both images and spectra. Unlike large, relatively inactive nuclei, this nucleus

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is outgassing near perihelion primarily due to CO_2, which drags large pieces of ice off the nucleus. It also shows substantial differences in the relative abundance of volatiles from various parts of the nucleus. These results have strengthened our view that comet nuclei are of modest size (R <20 km), high porosity (density of only about 350 kg m^{-3}), low strength (tensile strength on order of 10^3 dyn cm^{-2}), and are chemically heterogeneous. The Stardust results show the need for mixing of microscopic solids from 1 AU to several tens of astronomical units at an early phase of the protoplanetary disk prior to the accretion of comets. The Stardust-NExT mission returned to comet Tempel 1 on 14 February 2011, and imaged the nucleus, identifying a plausible feature at the Deep Impact site. These missions continue to stimulate 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 Hartley 2 nucleus were analyzed and discussed in papers published in *Astrophysical Journal Letters* (Volume 734, Issue 1, L1-8, June 2011) and in *Science* (Volume 332, pp. 1396-1400, June 2011), as well as a forthcoming special issue of *Icarus* in 2012. Due to space limitations here, only a few results can be included. For more details, see the excellent review of comet nuclei recently published by A'Hearn (2011).

Large flows with very smooth surfaces on the nucleus of Tempel 1 were seen in the Deep Impact images. There is some evidence that these layers are receding at the edges as predicted by the model of Britt *et al.* (2004) developed for the nucleus of comet Borrelly. The formation and morphologies of surface features appear to be driven by differential rates of sublimation erosion, which lead to active sites. Observations from the Stardust-NExT mission show that these layers receded in places by >10m between 2005 and 2011, further strengthening this view.

Another well-studied comet nucleus was 67P/Churyumov-Gerasimenko, the target of the Rosetta mission. Current mission status and science of Rosetta and many other spacecraft missions to small solar system bodies were presented at the B04 Event (Small Body Exploration: Past, Present, and Future Space Missions) at COSPAR 2010 in Bremen, Germany, during 21-23 July, 2010. A series of papers in published in a special issue of *Planetary and Space Science* describing its flyby of asteroid (2867) Steins (Vol. 58, Issue 9, July 2010, pp. 1057-1128). An up-to-date data set of the sizes and shapes of cometary nuclei is available from NASA's Planetary Data System (Paudel & Kolokolova 2010).

The latest analysis and results from SEPPCoN (Survey of Ensemble Physical Properties of Cometary Nuclei) of measuring thermal emissions of the sample nuclei have been published (Groussin *et al.* 2009; Licandro *et al.* 2009). This on-going survey involves studying 100 Jupiter-Family Comets (JFCs), about 25% of the known population, at both mid-infrared and visible wavelengths to constrain the distributions of sizes, shapes, spins, and albedos of this population. An important goal of SEPPCoN is to accumulate a large comprehensive set of high quality physical data on cometary nuclei in order to make accurate statistical comparisons with other minor-body populations such as Trojans, Centaurs, and Kuiper-belt objects. Information on the size, shape, spin-rate, albedo and color distributions is critical for understanding their origins and the evolutionary processes affecting them.

The size distribution of sun-grazing comets (members of the Kreutz family) has been investigated by Knight *et al.* (2010) using observations from the SOHO spacecraft coronagraphs. The estimated sizes are well fit by a power law of slope -2.2 over the range from several meters to several tens of meters, sharply steepening for larger sizes.

Modeling of comet nuclei focused on comet 67P/Churyumov-Gerasimenko, the Rosetta Mission target. A fully 3-dimensional model of comet nucleus evolution, including dust mantle formation was developed by Rosenberg and Prialnik (2009, 2010). Dust mantle thickness varies over the surface from 1 cm to about 10 cm. The water crystallization front advances inward in spurts, and its depth varies between 1 and several meters. Internal inhomogeneities affect both the surface temperature and the activity pattern of the comet. In particular, they may lead to outbursts at large heliocentric distances and also to activity on the night-side of the nucleus. Other groups have continued their quasi-three-dimensional thermal models for irregularly shaped cometary nuclei to interpret the current activity of comets in terms of initial characteristics, and to predict shape and internal stratification evolution of the nucleus (*e.g.*, Lasue *et al.* 2008; De Sanctis *et al.* 2009).

Gas coma, chemistry, plasma and tails — The study of compositional diversity among comets motivated several observational campaigns. Since A'Hearn *et al.* (1985), surveys of comets have provided taxonomies based on the abundance ratios of parent volatiles. To date, more than 20 molecules native to the nucleus ices are identified in comets. Measurements of nuclear spin ratios (in water, ammonia, and methane) and of isotopic ratios (D/H in water and HCN; $^{14}N/^{15}N$ in CN and HCN) have provided insights into the formation of the parent species. Identifications of abundant product species (*e.g.*, HNC) have provided evidence of gas-phase chemistry in the inner coma. Due to space limitations, only a few results are included here. For more details, see the excellent review of the chemistry of comets recently published by (Mumma & Charnley 2011).

The EPOXI results confirm that Comet Hartley 2 is enriched in CO_2 (nearly 20% relative to water) and that CO was unusually depleted (several tenths of a percent relative to water; Weaver *et al.* 2011). The production rate of water varied by a factor of two with nucleus rotation but CO_2 varied by a smaller factor, suggesting compositional heterogeneity of the nucleus. The production rates of other parent volatiles (H_2O, C_2H_6, HCN, CH_3OH) also vary with rotational phase (Dello Russo *et al.* 2011, Drahus *et al.* 2011, Mumma *et al.* 2011, Meech *et al.* 2011) but their abundance ratios remained constant during the EPOXI flyby. Mumma *et al.* (2011) suggest the presence of two separate ice phases (polar and apolar) in comet nuclei.

Mumma *et al.* (2011) obtained an ortho-para abundance ratio (OPR) in H_2O of 2.85 ± 0.20 in comet Hartley 2, consistent with statistical equilibrium (T_{spin} >32-55 K). Dello Russo *et al.* (2011) reported OPR=3.4 ± 0.3. In H_2O^+ and NH_2, OPRs provided spin temperatures of >25 K and 33 ± 3 K, respectively (Meech *et al.* 2011) and isotopic ratios for $^{12}C/^{13}C$ (95 ± 15) and $^{14}N/^{15}N$ (155 ± 25) in CN that were consistent with the mean values reported for other comets. Herschel achieved the first detection of HDO in a Jupiter-family comet (103P/Hartley 2; Hartogh *et al.* 2011). The D/H value of $(16.1\pm2.4)\times10^{-5}$ is the same as that in Earth's oceans and twice lower than values measured in Oort cloud comets. The reservoir of Earth-like water in the Solar System is significantly larger than previously thought.

Remote sensing can establish rough taxonomic classes of comets by measuring the volatile organic inventory of parent molecules at very low abundances (about 100 ppm relative to H_2O), including isotopic chemistry and nuclear spin ratios of molecules. More detailed compositional information is needed for the less-volatile organics. Stardust samples can provide this information for refractory organics but not for volatiles. The rendezvous of the Rosetta spacecraft with comet 67P/Churyumov-Gerasimenko in 2014 will measure the volatile fraction, while returned samples (such as the proposed Triple F and Comet Surface Sample Return missions) could provide this information as well.

Cometary atmosphere chemical modeling has been developed in several papers. Lederer *et al.* (2009a, 2009b) describe a three-dimensional, time-dependent Monte Carlo model developed to analyze the chemical and physical nature of a cometary gas coma including the necessary physics and chemistry to model comet Hale-Bopp at 1 AU from the Sun. Model calculations show that photoelectron impact excitation of CO and dissociative excitation of CO_2 can together contribute about 60-90% to Cameron-band emission in comet Hartley 2 (Bhardwaj and Raghuram 2011). 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. Boissier *et al.* (2010) find that an initial uniform surface flux of CO is assumed, the spiral structures created by the nucleus shape in the CO coma of comet Hale-Bopp are too faint to account for the observational data. Boice and Goldstein (2009) have applied their chemical model of cometary atmospheres to the plumes observed by the Cassini Mission at Enceladus. An extensive review of the expected plasma environment of comet 67P/Churyumov-Gerasimenko and current modeling capabilities has been given by Hansen *et al.* (2009).

Comets in the radio domain — Observations of comets in the radio and microwave domains are useful tools to probe the nucleus and dust thermal emission, and study the chemistry and kinematics of cometary atmospheres. The detection of the nucleus of 8P/Tuttle was achieved using the Plateau de Bure interferometer (Boissier *et al.* 2011). The abundances of a number of parent molecules (*e.g.*, HCN, CH_3OH, H_2S, CH_3CN) were measured in comets 73P, C/2002 T7, C/2002 X5, C/2002 VI and C/2006 P1, the latter four while being at distances <0.5 AU from the Sun (Hogerheijde *et al.* 2009; Paganini *et al.* 2010; Biver *et al.* 2011). Analysis of interferometric CO data on Hale-Bopp does not confirm the presence of an extended source of CO gas, as suggested by IR data (Bockele-Morvan *et al.* 2010). Reviews of the compositional diversity of cometary atmospheres, based on radio observations, have been published (Crovisier *et al.* 2009). Periodic variations of emission line profiles, related to nucleus rotation, were detected in comets Hale-Bopp, C/2001 Q4, 73P and 103P and used to investigate the rotational state of their nuclei and the presence of active spots (Bockele-Morvan *et al.* 2009, Boissier *et al.* 2010, Biver *et al.* 2011, Drahus *et al.* 2010, 2011). A few papers have been published presenting results based on Herschel observations. A number of water rotational lines were detected in comets 81P, C/2008 Q3 and 103P (Hartogh *et al.* 2010, Val de Borro *et al.* 2010, Meech *et al.* 2011).

Comet dust and distributed sources — Our understanding of the complexity of cometary dust has significantly progressed 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). Analyses of these data have continued during these past 3 years. 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.

Kelley & Wooden (2009) review the composition of JFC dust as inferred from infrared spectroscopy. They find that JFCs have 10μm silicate emission features roughly 20-25% above the dust continuum, similar to the weakest silicate features in Oort Cloud (OC) comets. Recent evidence suggests that grain porosity is different between JFCs and OC comets, but more observations and models of silicates in JFCs are needed. Models of observations from ground-based telescopes and the Spitzer Space Telescope have shown that JFCs have crystalline silicates with abundances similar to or less than those found in OC comets, although the crystalline silicate mineralogy of comets 9P/Tempel and C/1995 O1 (Hale-Bopp) differ from each other in Mg and Fe content. The heterogeneity of comet nuclei can be assessed with mid-infrared spectroscopy and evidence shows heterogeneous dust properties in the nucleus of comet 9P/Tempel. Models of dust formation, mixing in the solar nebula, and comet formation are constrained by the observed range of Mg and Fe content and the heterogeneity found in comet 9P/Tempel.

Recent successes of the Stardust Comet Sample Return and Hayabusa Asteroid Sample Return missions have demonstrated the powerful scientific insights that can be gained by bringing materials from extraterrestrial bodies to terrestrial laboratories for analysis. Such missions can establish the nature of extraterrestrial materials at a level of detail that can never be matched by in situ analyses, and analytical techniques can be used that do not suffer from the normal limitations of flight instrumentation. 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. Carbonaceous matter in Stardust samples returned from comet 81P/Wild 2 is observed to contain a wide variety of organic functional chemistry (de Gregorio *et al.* 2011).

Remote observations of the light scattered by the cometary dust coma are of major importance for determining the physical properties of the particles. Light scattering and especially linear polarization observations allow comparison between different coma regions and different comets, to retrieve physical properties of the dust particles, and to characterize their evolution around perihelion passage. Hadamcik *et al.* (2010) find that polarization and intensity variations in the coma of 67P/Churyumov-Gerasimenko are reminiscent of those noticed for some comets such as comet 81P/Wild 2 and comet 9P/Tempel 1. The presence of rather large particles can thus be suggested before and just after perihelion and the ejection of post-perihelion smaller grains, eventually in fluffy aggregates. A strong seasonal effect related to the obliquity of the comet suggests that the different grains originate in different hemispheres of the nucleus. Another important result, as far as light scattering by cometary dust is concerned, was related to polarimetric observations of the comet C/2007 N3 (Lulin). Woodward *et al.* (2011) find that large, low-porosity, absorptive aggregate dust particles best explain both the polarimetric and the mid-infrared spectral energy distribution.

The Wide-Field Infrared Survey Explorer (WISE) was launched on 14 December 2009. WISE imaged more than 99% of the sky in the mid-infrared for a 9-month mission lifetime. In addition to its primary goals of detecting infrared galaxies and brown dwarfs, WISE detected over 155,500 Solar System bodies, 33,700 of which were previously unknown. Most of the new objects were Main Belt Asteroids, with emphasis on the discovery of Near Earth Asteroids. Comets observed by WISE included both long and short-period orbits, including Hartley 2. Over 120 comets were imaged by WISE, with discoveris of 20 new comets. Observations of comets in the WISE thermal-infrared bands are being used to provide comet nucleus size constraints, estimate coma dust temperature and particle size distributions, and derive comet trail grain sizes and β-parameters.

Cometary material origins and laboratory experiments — 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). Kawakita and Kobayashi (2009) discussed constraints on the formation region of comets from their nuclear spin temperatures and D/H ratios. Relating to the origin of cometary materials, mechanisms of the outward transport of materials in the solar nebula are investigated theoretically (*e.g.*, Boss 2010; Ciesla 2009, 2011; and Hughes and Armitage 2010). 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). Marboeuf *et al.* (2010) have shown that clathrate hydrates could exist in short-period comet nuclei, *i.e.*, that the thermodynamic conditions in their interiors allow the existence of clathrate hydrates in Halley-type comets.

Many laboratory studies were carried out. Pat-El *et al.* (2009) performed an experimental study of the formation of an ice crust and migration of water vapor in a comet's upper layers. Gundlach *et al.* (2011) showed that observed gas production rates of pure hexagonal water ice could be reproduced experimentally. The reduction of the gas production rate due to an additional dust layer on top of the ice surface was measured and compared to the results of another experimental setup in which the gas diffusion through dust layers at room temperature.

Many experimental studies were also 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.*, Loeffler *et al.* 2011; Bennett et al. 2011; Hudson *et al.* 2009), while simple molecules or atoms were desorbed from the icy surfaces in some cases. Vigren *et al.* (2010) investigated dissociative recombination of protonated formic acid with implications for cometary chemistry.

Asteroids — More than 500 refereed papers dealing with the physical properties of the asteroids were published during the last triennium, between August, 2009 and October, 2011. The main areas covered in these publications were size distributions, masses and densities; photometry, shapes, and spin properties; radar, thermal IR, optical polarimetry, light-scattering phenomena; imaging, disk-resolved images, and binary systems; spectra, taxonomy, composition and space weathering; origins, impacts, families and evolutionary processes; space missions; asteroid-meteorite and asteroid-comet connections; near Earth asteroids (NEAs); trojan asteroids; and distant asteroids: Centaurs and TNOs.

Just as a few and certainly non-exhaustive examples of topics and papers of particular interest, we mention the discovery and continued characterization of the main belt comets (Hsieh & Jewitt (2006), Hsieh (2009-2011) Licandro *et al.* 2011), asteroid mass and density determinations (Zielenbach 2011), radar studies (Shepard *et al.* 2010), thermal IR (Lamy *et al.* 2010), polarimetry (Gil-Hutton & Cañada-Assandri 2011), water detection (Licandro *et al.* 2011), spectroscopy and composition (Reddy *et al.* 2010), space weathering (Willman *et al.* 2010), and light scattering (Muinonen *et al.* 2010). In addition, we also stress that the WISE mission, a satellite observing the sky at thermal IR wavelengths, has produced a major improvement in the field of thermal radiometry in the last triennium.

It is simply impossible to give a reasonable summary of all relevant activities in the space allocated to this report. The above-mentioned topics include all the traditional branches of investigations which make asteroid science so complex and interdisciplinary. In particular, the study of evolutionary processes, both physical and dynamical, are extremely important, since one of the ultimate goals of asteroid science is to be able to understand the properties of the primitive protoplanetary disk at the epoch of planetesimal growth, starting from the observable properties of the minor bodies as they are today. Processes including collisions and dynamical evolution triggered by physical properties, like the widely discussed Yarkovsky and YORP effects, have been the subjects of many investigations during the triennium. The traditional techniques of remote observation, including photometry and spectroscopy (both at visble and near-IR wavelengths), as well as polarimetry, high-resolution imaging and radar have been applied and the results have been described in many exciting papers. Significant advances have been made in the field of taxonomic classification, taking profit of the possibility to add near-IR reflectance spectra to the evidence coming from traditional spectroscopy and spectrophotometry at visible wavelengths. In this respect, there has been also an effort to produce practical tools to help observers in obtaining taxonomic classifications of object observed spectroscopically, by developing public facilities which can be found in the web. A good example is the Bus-De Meo spectrum classification facility available at http://smass.mit.edu/busdemeoclass.html. Other authors are also developing some similar tools, not limited to the field of spectroscopy and taxonomy, and this certainly is a very useful help for the activities in different branches of asteroid science.

3.2. *Meteors, Meteorites and Interplanetary Dust*

Significant advances were made as a result of meteorite falls. In particular, the Almahata Sitta meteorite was the first body to be observed and tracked in space, as asteroid 2008 TC3, prior to falling in the Nubian Desert of Northern Sudan on October 7, 2008. During a systematic search of the impact zone, some 600 fragments were recovered, most of which turned out to be ureilites, a rare meteorite type. A "Workshop on Asteroid 2008 TC3" was held at the University of Khartoum, Khartoum, Sudan, in December 2009, results of which were published in a special issue of *Meteoritics and Planetary Science* in 2010. Other recovered meteorite falls include the 9 April 2009 L6 ordinary chondrite Jesenice, Slovenia, the 26 September 2009 H5 ordinary chondrite Grimsby, Canada, the 28 February 2010 H5 ordinary chondrite Kosice, Slovakia, and the 13 April 2010 H5 ordinary chondrite Mason Gully, Australia. All recoveries were made as a consequence of the observed fireball, previously a rare event. This advance was a product of newly developed photographic and video camera fireball networks.

Significant advances in meteor astronomy were made from observations of meteor showers with radar and with security video cameras, networks of which provided precise orbit determinations. Some 83 meteor showers were added to the IAU C22 Working List of Meteor Showers. Particularly prolific was the Canadian Meteor Orbit Radar (CMOR), so far the best radar at separating showers from the sporadic background, and the video camera networks of SonotaCo in Japan, IMO in Europe, and CAMS in California. Results of CMOR included the detection of an outburst of Daytime Craterids, which were tentatively linked to hyperbolic comet C/2007 W1 (Boattini). CAMS detected the February eta Draconids, an outburst on February 4, 2011, caused by the dust trail of a yet undiscovered long period comet. Other unusual showers in this period included the 2009 and 2010 Orionids, now thought to be dust of 1P/Halley trapped in mean motion resonances. Newly established associations between meteor showers and parent bodies includes that of 169P/NEAT with the alpha-Capricornids. Thanks to the advanced application of theoretical dust trail calculations for meteor shower predictions, two observing campaigns were carried out during the 2009 Leonids and the 2011 Draconids. The Draconid shower was observed with two aircraft in a mission sponsored by CNRS and DLR. Both showers helped improve the models.

In part based on the meteor shower observations, the first dynamical model of the zodiacal cloud was constructed, showing the importance of (mostly dormant) Jupiter Family comets as a source of the interplanetary dust.

The re-entry of the spacecraft HAYABUSA over southern Australia on June 13, 2010, was observed as an artificial meteor experiment, both by ground-based observers and in a NASA sponsored airborne campaign. Scientific results have been published in the Special Issue "Re-entry of HAYABUSA spacecraft", Publication of Astronomical Society of Japan.

3.3. *Bioastronomy*

The primary activity of C51 is the triennial meeting. In 2011 for the first time this meeting was held jointly with a separate scientific society, the International Society for the Study of the Origin of Life – The International Astrobiology Society (ISSOL). The conference, called Origins 2011, http://www.origins2011.univ-montp2.fr/, took place July 3-8 in Montpellier, France. Thanks to an outstanding effort by the Scientific Organizing Committee (SOC), it was possible to retain the traditional C51 approach which supported only plenary sessions, so that all participants could fully participate in all sessions. The SOC had both nationality and gender balance, consisting of Alan Boss (USA), Andre Brack (France), Jose Cernicharo (Spain), Pascale Ehrenfreund (The Netherlands), Natalia Gontareva (Russia), Nils Holm (Sweden), Gerda Horneck (Germany), William Irvine (USA), Kensei Kobayashi (Japan), Ramanarayanan Krishnamurthy (USA), Antonio Lazcano (Mexico), Anny-Chantal Levasseur-Regourd (France), Claudio Maccone (Italy), Francois Raulin (France), Alan Schwartz (The Netherlands), and Janet Siefert (USA). The conference had 405 attendees, who gave 50 oral presentations and 320 poster presentations. Thanks to grants from NASA and ISSOL, 40 travel grants were made to young investigators, allowing them to attend the conference.

The success of Origins 2011 is evident from the decision of C51 and ISSOL to hold the next triennial conference also as a joint meeting. The C51 OC and the ISSOL Executive Committee agreed to accept an invitation from Japan, and the meeting will be in Nara, Japan, July 6-11, 2014. The Honorary Chair of the Local Organizing Committee is Norio Kaifu, President of the IAU, while the Chair is Kenji Ikehara, Director of the Nara Study Center and Past President of the Japanese Society for the Study of the Origin and Evolution of Life. The joint Chairs of the Scientific Organizing Committee will presumably be C51 OC member and presumed next Vice-President Sun Kwok from the University of Hong Kong (China) and Sandra Pizzarello (USA) from ISSOL. Current C51 President William Irvine plans to join ISSOL President David Deamer on a visit to the Nara venue in spring, 2012.

At the General Assembly in Beijing in 2012 C51 will be a primary sponsor of IAU Symposium 293, “Extrasolar Habitable Planets”, with the Chair of the SOC being Nader Haghighipour from the University of Hawaii (USA); and also of Special Session 16, “Unexplained Spectral Phenomena in the Interstellar Medium”, the SOC Chair being Sun Kwok from the University of Hong Kong (China). In addition, C51 is specifically supporting Special Session 14, “Communicating Astronomy with the Public for Scientists”, and Special Session 15, “Data Intensive Astronomy”.

4. Closing remarks

In spite of well known and widespread problems of financial support in these times of economic problems and consequent difficulties in getting dedicated manpower in many countries, the scientific community working in the field of the studies of comets and asteroids is extremely active and productive. This is a field of investigation which is very popular in many respects also in terms of public outreach, as a consequence of its intrinsic scientific importance and interest, as well as due to the fact of being strictly related to space missions which produce exciting results. These missions, which are based on the imagination and every-day activity carried out by a community of scientists from many countries, are also very useful to remind us that the mankind is able to obtain spectacular and breath-taking results when human genius is devoted to the study of Nature.

Karen Meech
president of the Division