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DIVISION F
COMMISSION 15

PHYSICAL STUDY OF COMETS AND MINOR PLANETS

ÉTUDE PHYSIQUE DES COMÈTES ET DES PETITES PLANÈTES

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LEGACY REPORT – 2015

Abstract. Commission 15 of the International Astronomical Union (IAU), entitled Physical Study of Comets and Minor Planets, was founded in 1935 and dissolved in 2015, following the reorganization of IAU. In 80 years of Commission 15, tremendous progress has been made on the knowledge of these objets, thanks to the combined efforts of ground- and space-based observations, space mission rendezvous and flybys, laboratory simulation and analyses of returned samples, and theoretical and numerical modeling. Together with dynamical studies of the Solar System, this discipline has provided a much deeper understanding of how the Solar System formed and evolved. We present a legacy report of Commission 15, which highlights key milestones in the exploration and knowledge of the small bodies of the Solar System.

1. Introduction

Small bodies are believed to be the remnants - either fragments or survivors - of the swarm of planetesimals from which the planets formed. As such they are primitive building blocks of the Solar System left over from formation processes that offer clues to the chemical mixture and conditions from which the planets formed some 4.6 billion years ago. By investigating in detail the physical and chemical properties of asteroids, comets, trans-Neptunian objects, and dwarf planets, one can characterize the conditions and processes of the Solar System's earliest epoch. This extends naturally also to some planetary satellites, which share, with small bodies and dwarf planets, similar properties and/or formation history and to studies of extra-solar systems. The scientific community has invested significant effort in past, ongoing, and future spacecraft missions and ground-based observations in support of these goals. Recently it has become increasingly evident that the differences between the small Solar System objects are much less sharp than previously believed so comparative studies are increasingly important.

Commission 15 had the responsibility for promoting scientific progress and research achievements in the fields of comets and asteroids, trans-Neptunian objects (TNOs), and dwarf planets in our Solar System and their relationships to other fields of astronomy. The activities are interdisciplinary, including applications of different theoretical approaches, making use of a variety of observing techniques and laboratory analyses, devoted to improving our understanding of the origin, evolution and current physical properties of small bodies orbiting at very different heliocentric distances.

2. Commission 15: an historical perspective

Commission 15, with the title “The Physics of Comets” (L’étude physique des comètes), was founded in 1935, during the 5^{th} General Assembly of the International Astronomical Union (IAU) occurring in Paris. Up to 1935, the study of comets was within the scope of Commission 16 “Planets, Comets, Satellites”. The report of the Commission 16 business meeting mentions: *A proposal to ask for a division of the scope of the commission by transferring the physical study of comets to another commission was considered. Only a few members vote, and the proposal was not carried.* As a matter of fact, Commission 15 met the first time in 1938, during the 6th IAU General Assembly hold in Stockholm, with Fernand Baldet, President, who issued the first report of Commission 15.

The enlargement of the scope of Commission 15 was decided in 1973, from the recognition that comets, minor planets (asteroids), and meteorites give closely related clues to the origin of the Solar System, and following an interim report of the General Secretary proposing a reorganization of Commissions 15, 16, 20, 21, and 22. The title of Commission 15 became “Physical Study of Comets, Minor Planets and Meteorites” (L’étude physique des comètes, petites planètes et des météorites).

Commission 15 was renamed “Physical Study of Comets and Minor Planets” following the 24th IAU General Assembly that took place in 2000. Activities about meteorites were transferred to Commission 22, which became entitled “Meteors, Meteorites, and Interplanetary Dust”.

Following the reorganization of the IAU structure in 2015, Commission 15 was dissolved. The proposal for pursuing the activities of Commission 15 was unsuccessful. At the end of its mandate, Commission 15 comprised 408 members.

Table 1 lists presidents and vice-presidents of Commission 15, and references to issued triennium reports when available online.

Here is a message from Walter Huebner, president of Commission 15 in 2006–2009: *Astronomy is a subject that provides abstract knowledge about the universe. It has also provided very useful information to humanity about the Solar System. Commission 15 has supported astronomical observations about asteroids and comets, making precise orbital determinations of these objects possible. It has also made it possible to estimate their size from albedo measurements, their composition from spectroscopic observations, and many other properties. This information is crucial for implementing countermeasures should such an object threaten to impact Earth. It is unconscionable for the IAU to shirk its responsibility on these endeavors.*

3. Working Groups and Task Groups

During the business meeting that took place in 1985, three working groups were established: Working Group on Comets, Working Group on Minor Planets, and Working Group on Meteorites, with the aim that these working groups coordinate the related activities, and assist the president in preparing the triennium report. The first two Working Groups

Table 1. Overview of Commission 15 leadership and triennium reports (as available in ADS) from 1935 onward. Reports flagged with an asterisk appear not to be available on line or not available.

Years	President and Vice President	ADS bibcode
1935-1938	F. Baldet	*
1948-1952	Dr McKellar	*
1952-1955	P. Swings	*
1955-1958	P. Swings	*
1958-1961	K. Wurm	*
1961-1964	K. Wurm, F. L. Whipple	*
1964-1967	F. L. Whipple, L. Biermann	*
1967-1970	L. Biermann, V. Vanýsek	1970IAUTA..14...141B
1970-1973	V. Vanýszek, A. H. Delsemme	1973IAUTA..15...179V
1973-1976	A. H. Delsemme, N. B. Richter	1976IAUTA..16a...61D
1976-1979	N. B. Richter, B. D. Donn	1979IAUTA..17b..73R
1979-1982	B. D. Donn, B. Levin	1982IAUTA..18...153D
1982-1985	C. R. Chapman, L. Krezak	1985IAUTA..19...167C
1985-1988	L. Krezac, J. Rahe	1988IAUTA..20...143K
1988-1991	J. Rahe, A.W. Harris	1991IAUTA..21...137R
1991-1994	A.W. Harris, M. A'Hearn	1994IAUTA..22...135H
1994-1997	M. A'Hearn, V. Zappalà	1997IAUTA..23..183A
1997-2000	V. Zappalà, H.U. Keller	*
2000-2003	H.U. Keller, E.F. Tedesco	2003IAUTA..25..147K
2003-2006	E.F. Tedesco, W. Huebner	2007IAUTA..26...121T
2006-2009	W. Huebner, A. Cellino	2009IAUTA..27...154H
2009-2012	A. Cellino, D. Bockelée-Morvan	*
2012-2015	D. Bockelée-Morvan, R. Gil-Hutton	*(this report)*

remained in activity until Commission 15 was dissolved (with D. Boice and D. Tholen as chairs of the comets and minor planets working groups, respectively, for 2012–2015), whereas the Working Group on Meteorites was moved to Commission 22.

In 2003, three task groups were set up in Commission 15: A Task Group on Asteroid Magnitudes (TGAM), co-led by E. F. Tedesco and R. A. Gil-Hutton; a Task Group on Asteroid Polarimetric Albedo Calibration (TGAPAC), co-led by A. Cellino and R. A. Gil-Hutton; and a Task Group on Comet Magnitudes (TGCM), co-led by G. Tancredi and T. Yamamoto. A fourth Task Group for Geophysical and Geological Properties of Asteroids and Comet Nuclei (name changed to Task Group for Physical Properties of Near-Earth Objects TGPPNEO in 2009) was 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 were also of great importance for the development of countermeasures against potentially hazardous objects.

The major goal of TGPPNEO was to collect knowledge and data on material properties (observed or simulated) of NEOs: a database was established at neodata.space.swri.edu, updated till 2009. The Near Asteroid Data Base, a service from the European Asteroid Research Node, maintained at DLR and sponsored by ESA, contains published data on all known NEOs and corresponding references. Radar properties are available at echo.jpl.nasa.gov/asteroids/index.html, whereas spectral properties are referenced at smass.mit.edu/catalog.php.

Task groups TGCM and TGPPNEO ended in 2012. Final reports of the Task groups TGAPAC and TGAM, chaired by A. Cellino and K. Muinonen, respectively, are given at the end this Legacy paper.

4. Links to other commissions, divisions

Throughout the history of Commission 15, there were always strong synergies with several other commissions. Physical studies of small bodies has important implications to their dynamics (Commissions 20 and 4), astrobiology (Commission 51), meteors (Commission 22), relationships with planetary moons (Commission 16), extrasolar planetary systems (Commissions 53), conditions of the solar nebula and connections to the Interstellar Medium (Commission 34), and commissions in Division E (Sun and Heliosphere). Joint meetings were organized at several occasions. Through these links, Commission 15 has provided great service to the society and to the astronomical community at large.

5. Publications, and related meetings

5.1. *Publications*

For this legacy report, we took the opportunity to review the community publication activity. For this, we used the Astrophysics Data System (ADS) which enables searches over all the major trade publications in astrophysics in general. Since the publication rate at the scale of the year will be influenced by the impact of small time-scale events (such as a particularly bright comet, the flyby or rendezvous of an asteroid or a comet by a space mission, the Shoemeker-Levy 9 event), we queried refereed publications in ADS by ranges of five years (i.e, 1935-1940, 1940-1945, etc) and divided the returned number of publication by five, to obtain an average rate of publication per year (over a 5-year period). Distinct queries were done for comets, asteroids, and trans-Neptunian objects using “comets”, “asteroids”, and “trans-Neptunian+Kuiper” as abstract words/keywords. It is clear that this approach might overestimate the number of publications related to Commission 15, as articles related to the dynamics and orbits of the objects (in the scope of Commission 20) were also returned. Only publications later than 1990 were considered for trans-Neptunian objects, since the first object of this population was discovered in 1992.

The evolution of the publication rate for the three categories of objects is shown in Figure 1. The rise in publications related to comets accelerated in the period 1985–1990, which coincides with the space exploration of comet 1P/Halley by an armada of missions (Table 4). The peak present for 1995–2000 is likely related to the passage of the bright comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp). The interest in the physical study of asteroids really started in the 1970s, attracting then a growing community of researchers. Indeed, the development of CCD sensitive photometry, together with the availability of larger optical telescopes enabled intensive observations of asteroids, and the start of a classification based on spectra, colors, and sometimes albedo when IR measurements where available (Chapman *et al.* 1975, Tholen *et al.* 1984). The NASA Spaceguard program, primarily aimed to discover and study near-Earth objects, initiated a number of dedicated sky surveys which resulted in enlarging the number of known asteroids (and comets), for statistical analysis (Fig. 2). Sustained research on asteroids since 1990 is largely related to their space exploration, with not less than twelve asteroids visited by spacecrafts (Table 5). The number of papers related to the physical characterization of trans-Neptunian objects rapidly grew in the 2000s thanks to the availability of 10-m class telescopes, allowing the measurement of the colors and spectra of these faint objects, and the rapid growth of the number of identified objects.

5.2. *Meetings*

The community exchanges information efficiently at scientific meetings. The Division of Planetary Sciences (DPS) of the American Astronomical Society (AAS) organizes an

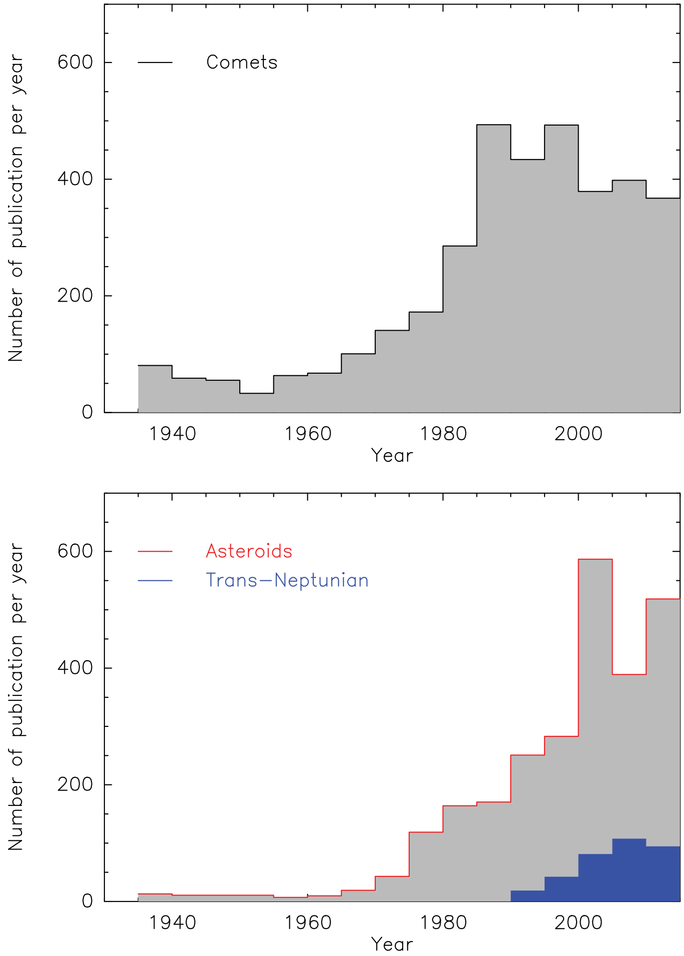


Figure 1. Number of refereed publications per year related to the study of comets (top), asteroids and trans-Neptunian objects (bottom), as returned from ADS. Queries were done by intervals of five years, and the returned number of publications was divided by 5.

international meeting each year, with a large number of sessions focussing on small Solar System bodies. The European Planetary Science Congress (EPSC), created in the frame of Europlanet, is the largest meeting in Europe dedicated to planetary science, and had its first meeting in 2006. Sessions dedicated to small bodies are also taking place during the annual meetings of the American Geophysical Union (AGU), European Geophysical Union (EGU), Committee of Space Research (COSPAR), and Asia Oceania Geoscience Society (AOGS).

More specific meetings are numerous, and we list in Tables 2 and 3 IAU meetings directly or closely related to the physical study of comets and asteroids. Comets were the topic of several "Colloque International d'astrophysique de Liège" in the 50s and 60s. An important meeting for Commission 15 members is "Asteroids, Comets and Meteors" (ACM), which takes place every three years since 1983. This meeting was initiated by C.I. Lagerkvist and H. Rickman, with the first three meetings held in Uppsala. Two ACM meetings were supported by IAU.

Table 2. List of IAU symposia related to Commission 15.

Symposium	Year, Location	Title
IAUS 045	1970, Russia	The Motion, Evolution of Orbits, and Origin of Comets
IAUS 065	1973, Poland	Exploration of the Planetary System
IAUS 090	1979, Canada	Solid Particles in the Solar System
IAUS 160	1993, Italy	Asteroids, Comets, Meteors 1993
IAUS 197	1999, Rep. of Korea	Astrochemistry: From Molecular Clouds to Planetary Systems
IAUS 202	2000, UK	Planetary Systems in the Universe - Observation, Formation and Evolution
IAUS 229	2005, Brazil	Asteroids, Comets, Meteors - ACM 2005
IAUS 236	2006, Czech Republic	Near Earth Objects, our Celestial Neighbors: Opportunity and Risk
IAUS 251	2008, China PR	Organic Matter in Space
IAUS 263	2009, IAU GA Brazil	Icy Bodies in the Solar System
IAUS 276	2010, Italy	The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution
IAUS 299	2013, Canada	Exploring the Formation and Evolution of Planetary Systems

Table 3. List of IAU Colloquia related to Commission 15.

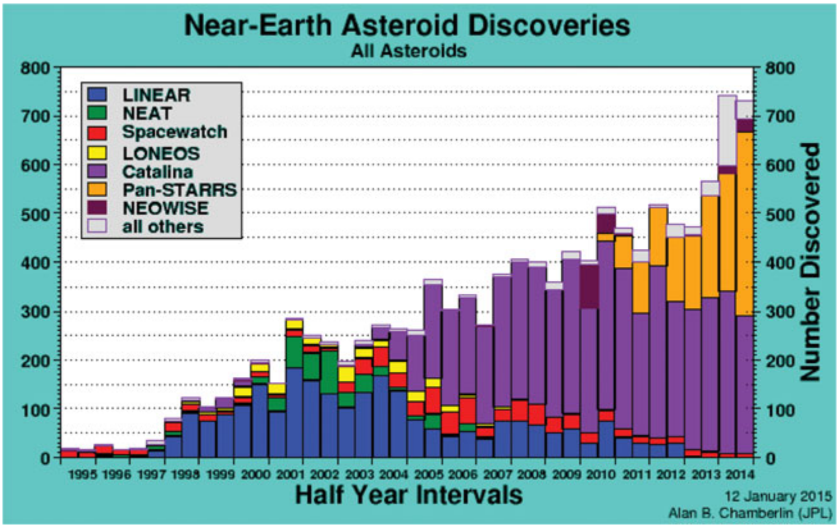
Colloquium	Year, Location	Title
IAUC 012	1971, USA	Physical Studies of Minor Planets
IAUC 022	1972, France	Asteroids, Comets, Meteoritic Matter
IAUC 025	1974, USA	The Study of Comets
IAUC 039	1976, France	Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins
IAUC 052	1978, USA	Protostars and Planets: Studies of Star Formation and the Origin of the Solar System
IAUC 061	1981, USA	Comets, Gases, Ices, Grains and Plasmas
IAUC 116	1989, Germany	Comets in the Post-Halley Era
IAUC 126	1990, Japan	Origin and Evolution of Interplanetary Dust
IAUC 156	1995, USA	The impact of Comet Shoemaker-Levy 9 on Jupiter
IAUC 168	1998, China	Cometary Nuclei in Space and Time
IAUC 181	2000, UK	Dust in the Solar System and Other Planetary Systems
IAUC 186	2002, Spain	Cometary Science after Hale-Bopp

6. Small bodies : evolution of observing tools

6.1. *Remote sensing from ground and space*

The last century and decades have seen considerable changes in observing techniques and available facilities, that have covered all fields in astronomy.

Large programmes and survey programmes, not forgetting the important contribution of amateur astronomers, considerably enlarged the catalogue of known and detected objects. To illustrate this fact, it is worth remembering that in 1935 there were about 1200 numbered minor planets (asteroids), and 32 named periodic comets. In 1935, only four comets were discovered: 32P/Comas-Solà and three long-period comets. Nowadays, 50 comets are typically discovered per year and the number of catalogued periodic comets in mid-2015 was 329. Figure 2 illustrates the progress in near-Earth asteroid discovery thanks to dedicated surveys. To date, the vast majority of the known asteroids have



12 January 2015
Alan B. Chamberlin (JPL)

Figure 2. Discovery statistics of NEOs obtained from telescopes dedicated to asteroid searches. From A. B. Chamberlin, neo.jpl.nasa.gov.

been discovered by dedicated surveys funded by NASA. The ability of these surveys to find small asteroids has also steadily improved, with eight times more near-Earth objects and ten times more main-belt asteroids found in 2010–2015 than the 5 years covering 1997–2002. Asteroid surveys are also responsible of 3/4 of the newly discovered comets, the rest coming from amateur astronomers.

The invention of CCDs cameras in the 80s had an essential role in advancing our understanding of asteroidal surfaces and rotation, enabling the number of objects for which high-quality spectra are available to grow to thousands. The use of very large telescopes, of radar and radio antennas, as well as space-based facilities enabled to reach more and more distant and smaller bodies, or even to resolve those asteroids (that are no more starlike). This enabled the discovery and physical characterization of different classes of asteroids, improving the taxonomy, the detection of collisional families, and of non-gravitational effects (e.g., the Yarkovsky-O'Keefe-Radzievskii-Paddack effect). The sample of known near-Earth objects, binary and multiple systems, increased, and new objects were found, such as Trojans around planets other than Jupiter, Centaurs (including active Centaurs) and trans-Neptunian objects.

The availability of infrared telescopes (ISO, IRAS, Spitzer, Herschel, WISE, NEOWISE from space, airborne telescopes, KAO, SOFIA, and ground-based telescopes IRTF, VISTA, ...) and the application of large aperture telescopes allowed the understanding of the thermal properties of asteroids, trans-Neptunian and near-Earth objects. Advances in radar imaging, and radar reconstruction techniques provided important information about the physical properties and orbits of near-Earth and main-belt asteroids. Adaptative optics allowed imaging the largest asteroids, complementing observations with the Hubble Space Telescope.

The sensitivity of 10-m class optical telescopes was crucial for the study of the surface composition of trans-Neptunian objects and Centaurs. A new era just opened with the imaging of asteroid Juno by the Atacama Large Millimeter/submillimeter array (ALMA). The understanding of the diversity of the trans-Neptunian population was possible thanks to the establishment of large spectral/photometric surveys, e.g., the "ESO survey", and the "TNOs are cool" key program with Herschel.

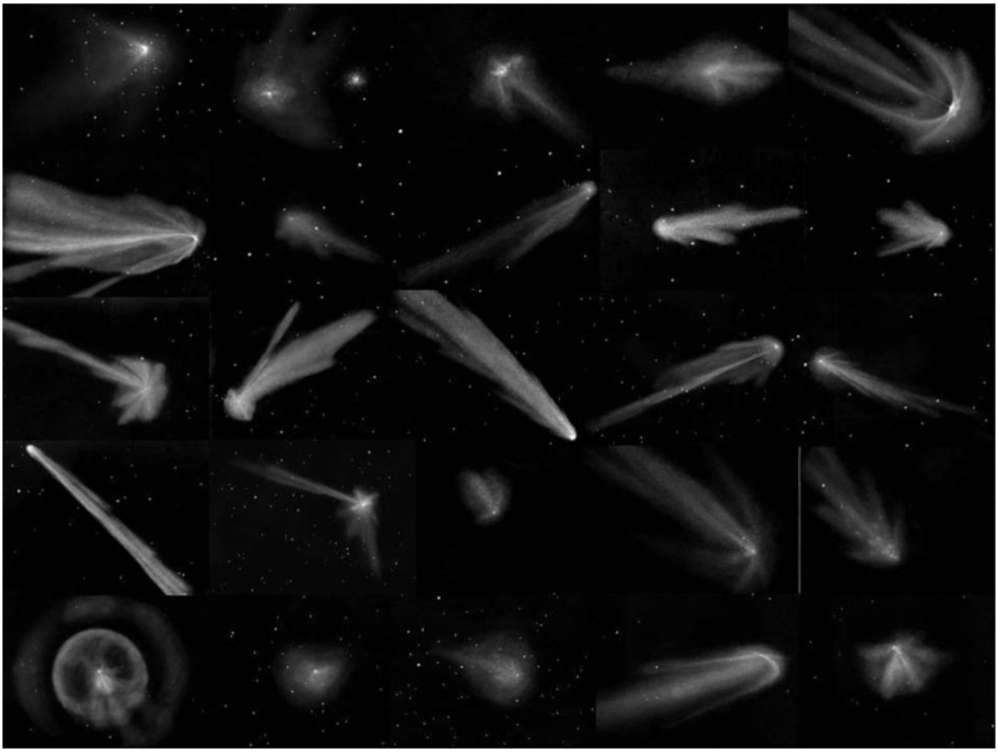


Figure 3. Nicolas Bivers's sketches of comets that had their perihelion between 1989–2010. From left to right, and top to bottom: C/1989 X1 (Austin), C/1990 K1 (Levy), 109P/Swift-Tuttle, 19P/Borrelly, C/1996 B2 (Hyakutake), C/1995 O1 (Hale-Bopp), 21P/Giacobini-Zinner, C/1999 H1 (Lee), C/1999 S4 (LINEAR), C/1999 T1 (McNaught-Hartley), C/2001 A2 (LINEAR), C/2000 WM1, 153P/Ikeya-Zhang, C/2001 Q4 (NEAT), C/2002 T7 (LINEAR), C/2002 V1 (NEAT), C/2004 Q2 (Macholz), 9P/Tempel 1, 73P-C/Schwassmann-Wachmann 3, 73P-B/Schwassmann-Wachmann 3, 17P/Holmes (after its extraordinary outburst in 2007), 8P/Tuttle, 103P/Hartley 2, 81P/Wild 2, and 10P/Tempel 2.

Progress in the understanding of comet composition benefitted dramatically from advancements in millimeter/submillimeter and infrared techniques. Most known molecules (about 30 molecules) were identified by observations in these windows. The development of sensitive high-resolution infrared spectroscopy in the 90s opened a new era for the study of comet chemistry. The distribution of gases in the inner coma can now be investigated by millimeter interferometry (IRAM, ALMA). High-resolution spectroscopy in the near-UV provided key information on isotopic ratios. Several space observatories were key tools to investigate comet properties, such as the Hubble Space telescope (1990–), the International Ultraviolet Explorer (IUE, 1978–1996), the Infrared Space Observatory (ISO, 1996–1998), Spitzer (2003–2009), the Herschel space observatory (2009–2013). ISO also allowed to study the thermal properties of cometary dust, and to unravel the silicate composition of grains from their medium-IR signatures.

Huge progress in the understanding of dust properties benefitted from systematic polarimetric observations of the solar light they scatter. Giotto provided clues to changes in dust properties within Halley coma and to extremely low densities of dust particles (Levasseur-Regourd *et al.*, 1999; Fulle *et al.*, 2000). Polarimetric remote observations, including data retrieved from polarimetric imaging, suggested the presence of both fluffy

Table 4. List of space missions to comets.

Comet	Mission	Date	Closest approach (km)	Velocity km/s
21P/Giacobini-Zinner	ICE	11 September 1985	7800	21
1P/Halley	VEGA 1	6 March 1986	8890	79
1P/Halley	Suisei	8 March 1986	150 000	73
1P/Halley	VEGA 2	9 March 1986	8030	77
1P/Halley	Sakigake	11 March 1986	7 000 000	75
1P/Halley	Giotto	14 March 1986	596	68
1P /Halley	ICE	28 March 1986	28 000 000	–
26P/Grigg-Skjellerup	Giotto Extended	10 July 1992	<200	14
19P/Borrelly	Deep Space 1	22 September 2001	2170	17
81P/Wild 2	Stardust	2 January 2004	236	6
9P/Tempel 1	Deep Impact	4 July 2005	500	11
103P/Hartley 2	EPOXI	4 November 2010	694	12
9P/Tempel 1	Stardust-NEXT	15 February 2011	181	11
67P/Churyumov-Gerasimenko	Rosetta	2014-2016	10–1500	~ 0

aggregates and compact particles within the dust population (Hadamcik *et al.*, 2002; Lasue *et al.*, 2009).

In a number of circumstances, worldwide observational campaigns from ground- and space observatories were organized. Several of them provided support to space missions, such as the International Halley Watch from 1982 to 1987 (Newburn & Rahe 1984), the coordinated campaign of the Deep Impact collision with 9P/Tempel 1 (Meech *et al.* 2005), and that of comet 67P/Churyumov-Gerasimenko in support to the Rosetta Mission (C. Snodgrass, coordinator). In other cases, the campaigns were organized for best study of unusual events: e.g, the NASA Near-Earth object program office coordinated observations of the perilous approach to the Sun of comet C/2012 S1 (ISON). The first international multi-wavelengths observing campaign was in 1973–1974, for comet C/1973 E1 Kohoutek. Particularly important was the worldwide campaign for the collision of the fragments of comet Shoemeker-Levy 9 with Jupiter, which mobilized most telescopes in the world in a short notice. The large participation of amateur astronomers contributed to the success of these campaigns. The establishment of coordinated observing campaigns, some of them discussed during Commission 15 meetings, had also a great impact for approval and scheduling by program committees. Figure 3 show sketches of bright comets which had their perihelion in 1989–2010, and were intensively observed.

6.2. *Space missions to small bodies*

In situ observations of asteroids and comets have strikingly propelled our knowledge forward by allowing us to explore these bodies as real places (Figs. 4 and 5), and return precious samples of their material (see the review of Barucci *et al.*, 2011). With space missions our understanding of these bodies was revolutionized, in particular their physical properties, surface properties, constitution, shapes, gravity, etc... Some interplanetary spacecraft (e.g., Pioneer, Voyager) crossed the main asteroid belt without any rendezvous opportunity. The first – and majority of - space missions visiting small bodies consisted in a 'simple' flyby, and brought the first image of an asteroid, namely (951) Gaspra, the discovery of a natural satellite in orbit around Ida, the first precise mass determinations

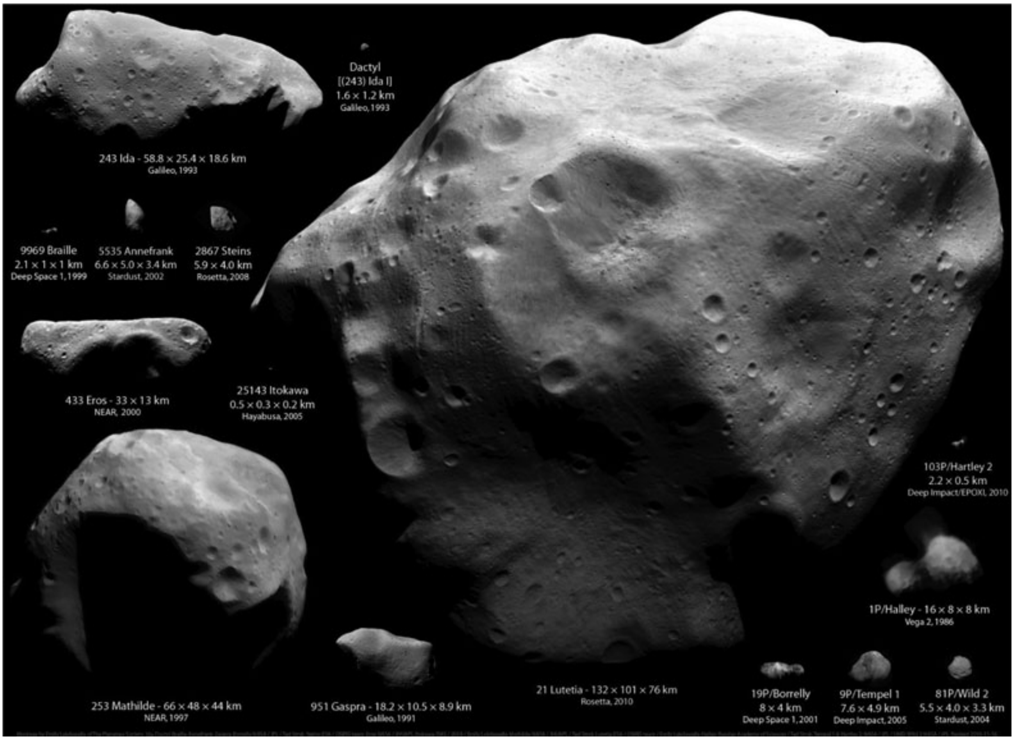


Figure 4. Asteroids and comets imaged by spacecraft. Not included, 67P explored by Rosetta; Vesta and Ceres, explored by Dawn; and Pluto explored by New Horizons.

from the gravitational perturbations, and measurement of bulk densities. The armada of missions towards comet 1P/Halley (Table 4), not only revealed the nucleus of a comet and some of its physical properties, but also brought important information on the nature of the dust and gas atmosphere and its interaction with the solar wind.

An excellent overview of the spacecraft exploration of asteroids is provided by Farquhar *et al.* in the Asteroids III book, covering the period up to 2001. The list of asteroids visited by spacecraft is given here in Table 5. In 2005, the JAXA Hayabusa Mission visited a 320-m-sized near-Earth asteroid (NEA) named Itokawa, which turns out to be a rubble pile, and successfully returned a sample to Earth. In 2008 and 2010, the European Space Agency (ESA) Rosetta Mission performed flybys of the E-type asteroid Steins, and the M-type asteroid Lutetia, which was found to have an intriguingly high density of 3.4 g.cm^{-3}. Before the space probe NEAR visited – on its route to Eros – the main-belt asteroid (253) Mathilda revealing surprisingly large craters and very low bulk density of 1.3 g.cm^{-3} suggesting it to be a loosely packed gravitational aggregate or “rubble-pile”. In 2011–2012, the NASA Dawn Mission orbited Vesta, the second largest asteroid (530 km diameter), and is now orbiting Ceres, the largest one (950 km diameter). These two worlds provide potential windows into the nature of the protoplanets that accreted into the terrestrial planets and perhaps those large bodies found today in the Kuiper belt. The OSIRIS-REx and Hayabusa 2 missions will return samples of pristine carbonaceous material to Earth for detailed analysis.

Space missions to comets are listed in Table 4. Space missions are the only means of studying the details of a cometary nucleus, the nucleus being hidden by the dust and gas coma. In addition, they allow investigations of the near-nucleus coma and relationships

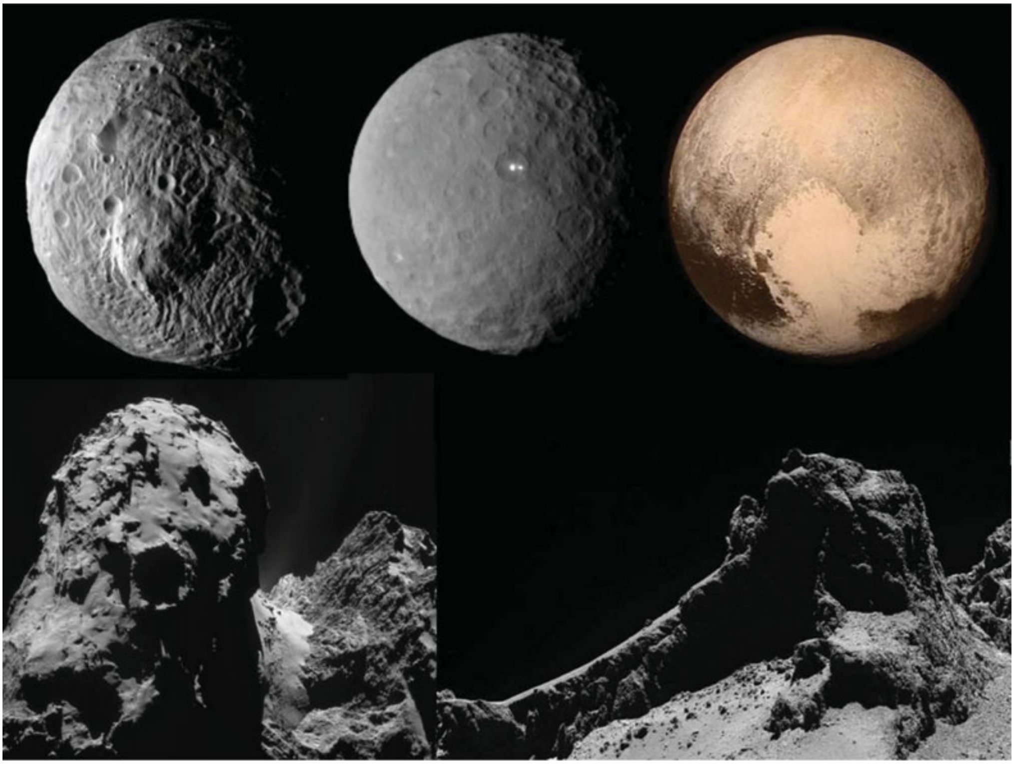


Figure 5. Images from space missions. Top, from left to right : Vesta, Ceres, explored by Dawn, Pluto explored by New Horizons (credit NASA). Bottom: 67P explored by Rosetta (credit NAVCAM/ESA, MPS/ESA).

between the coma and nucleus properties. Spacecraft flybys of comets dramatically improve our understanding of the physical and outgassing properties of cometary nuclei, starting with Vega and Giotto missions in the 80s to Deep Space 1, Deep Impact (and its extended mission, EPOXI) and Stardust (and its extended mission Stardust-NExT) in the 2001–2011 period. Stardust collected grains of comet Wild 2, for analysis in terrestrial laboratories. This mission provided important insights on the nature of cometary material, in particular about the presence of minerals formed in hot environments near the newly-born Sun.

A major step forward our understanding of comets is being accomplished with the Rosetta Mission. Launched in 2004, Rosetta arrived to the vicinity comet 67P/Churyumov-Gerasimenko in August 2014 and is following the comet on its trajectory up to October 2016. On 12 November 2014, the Philae probe carried by Rosetta achieved the first-ever soft landing on a comet nucleus. With about ten instruments on both Philae and Rosetta, this mission has provided many new discoveries of the processes taking place on cometary nuclei, and on the composition of comets. At the time of writing, many papers were already published in *Science* and *Nature*. A special issue of *Astronomy & Astrophysics* is devoted to Rosetta results.

Finally, on 14 July 2015, the New Horizons Mission, launched in 2006, flew by Pluto and Charon, revealing youthful and varied terrains. New Horizons is now on its path to flyby a small Kuiper-Belt object (KBO).

Table 5. List of space missions to asteroids and dwarf planets.

Object	Mission	Date	Closest Approach (km)
(951) Gaspra	Galileo	29 October 1991	1600
(243) Ida	Galileo	28 August 1993	2400
(253) Mathilde	NEAR/Shoemaker	17 June 1997	1212
(9969) Braille	Deep Space 1	20 July 1999	26
(433) Eros	NEAR/Shoemaker	1998, 2000–2001	0
(2685) Masursky	Cassini/Huygens	23 January 2000	1 600 000
(5535) Annefrank	Stardust	2 November 2002	3100
(25143) Itokawa	Hayabusa	September-November 2005	0
132524 APL	New Horizons	13 June 2006	102 000
(2867) Steins	Rosetta	5 September 2008	800
(21) Lutetia	Rosetta	10 July 2010	3162
(4) Vesta	Dawn	2011–2012	210
(4179) Toutatis	Chang'E-2	13 December 2012	1.9
(1) Ceres	Dawn	March 2015 –	$<$ 1000
(134340) Pluto	New Horizons	14 July 2015	12 500
(162173) Ryugu	Hayabusa 2	*expected* 2018	
(101955) Bennu	OSIRIS-Rex	*expected* 2018	
(2140) MU_{69}	New Horizons	*expected* 2019	

Table 6. Books from the University of Arizona Press.

Book	Year	Editors
Asteroids	1979	T. Gehrels ed.
Comets	1982	L.L. Wilkening ed.
Asteroids II	1989	R. Binzel, T. Gehrels, M.S. Matthews eds.
Pluto & Charon	1997	S.A. Stern & D.J. Tholen eds.
Asteroids III	2002	W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel eds.
Comets II	2004	M.C. Festou, H.U. Keller, H.A. Weaver eds.
The Solar System beyond Neptune	2008	M.A. Barucci, H. Boehnhardt, D.P. Cruikshank, A. Morbidelli eds.
Asteroids IV	2015	P. Michel, F.E. DeMEo, W. F. Bottke eds.

6.3. *Heliospheric space missions related to near-Sun comets*

Our knowledge of comets is primarily based on observations of these bodies when they are 1 AU or more from the Sun. However, most known comets reach perihelion much nearer to the Sun, experiencing extreme solar wind and insolation conditions, and, in the case of sungrazers, often undergoing complete destruction. Observations of their spectra, temporal behavior, and tails in this environment reveal valuable information on their internal structure and composition that is complementary to that from comets observed in more benign conditions. The Kreutz group is the best-studied family of sungrazers (see, e.g., Knight *et al.* 2010). Its members include the most spectacular comets in history, the Great Comet of 1882, Ikeya-Seki (1965f) (Marsden 1989), and recently, comet Lovejoy (C/2011 W3). Optical spectra of Ikeya-Seki contain emissions from metallic neutrals and ions (Na, Ca, Ca^+, K, Cu, Fe, V, Mn, Ni, Co) indicating sublimation of refractory comet grains as well as the normal cometary species (C_2, C_3, CH, CN, NH_2) (Preston 1967, Slaughter 1969). Kreutz sungrazers are thought to have fragmented from a single parent body as indicated by their orbital similarities. Almost 3000 Kreutz comets have been observed in SOHO and STEREO images since 1996. Their sizes are estimated at 100-m or smaller (Iseli *et al.* 2002, Sekanina 2003) and do not seem to survive perihelion (Biesecker *et al.* 2002). Comet Lovejoy was the first Kreutz sungrazer since 1970 to survive perihelion passage but the extent to which the nucleus survived is unclear (Knight *et al.* 2012). In addition, comet C/2012 S1 (ISON) treated us to another spectacular sungrazer in late 2013 that was extensively observed by ground- and space-based observatories (Lisse *et al.* 2014), until its disruption after perihelion. At present, observations of sungrazers are challenging, and are primarily made by space- and ground-based instruments designed for the study of the Sun, its corona, and the inner heliosphere. The wealth of this multi-wavelength data provides unprecedented opportunities to gain insights in the processes acting on a comet in the harsh near-Sun environment. Despite the enormous scientific value of such comet observations and their interpretation for our understanding of our Solar Systems makeup and origins, no comprehensive understanding of near-Sun comets has been compiled to date.

Near-Sun comets can be defined as those approaching closer to the Sun than Mercury (0.31 AU). Almost all such comets are sungrazers or long-period comets. Most sungrazers belong to one of a few distinct groups of comets sharing similar orbital elements; many of these are completely destroyed during their perihelion passages; a recent exception being C/2011 W3 (Lovejoy), which at least partially survived to become a bright naked-eye comet post-perihelion in December 2011-January 2012. By far the most common family is the Kreutz group; others include the Meyer, Kracht, and Marsden groups. The orbital element groupings strongly suggest a limited number of progenitor objects. Currently, almost 3000 comets have been discovered with SOHO/LASCO, the vast majority of which are Kreutz sungrazers. Prominent long-period comets that have approached close to the Sun include C/1996 B2 (Hyakutake), C/2002 V1 (NEAT), and C/2006 P1 (McNaught). In addition, short-period comet 96P/Machholz's reaches perihelion at 0.12 AU, and may be related to the Kracht and Marsden groups (Ohtsuka *et al.* 2003). Machholz's unusual composition suggests an origin different to most other known comets (Schleicher 2008). Several non-sungrazers have been discovered early enough prior to perihelion to allow dedicated observations by the LASCO coronagraph using the instrument's broadband color filters. Those that pass close enough to the Sun can be observed by UVCS, which provides ultraviolet spectra (Povich *et al.* 2003).

Much of our knowledge of near-Sun comets has been gleaned by instruments carried by SOHO since its 1996 launch. Three instruments have provided extremely valuable cometary data: the Large Angle and Spectrometric Coronagraph, LASCO (Brueckner *et al.* 1995), the Ultraviolet Coronagraph Spectrometer, UVCS (Kohl *et al.* 1995), and Solar Wind Anisotropies, SWAN (Bertaux *et al.* 1995). Since 2006, the near-Sun environment has also been monitored by the twin STEREO spacecraft, which carry an instrument suite, SECCHI, to observe the Sun and heliosphere to a distance of 1 AU in the direction of the Earth (Howard *et al.* 2002). The Solar Dynamics Observatory has recently demonstrated visibility of very bright sungrazers at EUV wavelengths (Schrijver *et al.* 2012). The recent study of Downs *et al.* (2013) demonstrates the information that can be gained of the magnetic field of the solar corona by advanced modeling of this data. Ground-based observatories also perform suitable observations in some cases (e.g., Snodgrass 2007), including the extensive observational campaign for comet ISON (Lisse *et al.* 2014).

7. Small bodies: key milestones

Summarizing 80 years of research and discoveries on small Solar System bodies in this report is an impossible task. Triennium reports published in the IAU Transactions A (see Table 1 for those published online) provide a good historical perspective of the evolution

Table 7. Milestones in cometary research. Concepts and models are in italics.

Year	Highlight	Reference
1941	Discovery of OH 309 nm emission	Swings (1941a)
1941	Modelling of CN fluorescence, Swings' effect	Swings (1941b)
1943	*Parent compounds in the nucleus*	Wurm (1943)
1950	*The Oort cloud*	Oort (1950)
1950	*The icy conglomerate model*	Whipple (1950)
1950	Non-Gravitational forces evidenced	Whipple (1950)
1951	Solar wind interaction with ion tails	Biermann (1951)
1952	*The clathrate hypothesis*	Delsemme & Swings (1952)
1957	*The theory of plasma tails*	Alfven (1957)
1957	*Model of the distribution of gases*	Haser (1957)
1967	Optical spect. of metals in sungrazing comet Ikeya-Seki	Preston (1967)
1968	*Theory of dust tails*	Finson & Probstein (1968)
1969	*Non-gravitational forces in comet dynamics*	Marsden (1969)
1970	First detection of Lyman α emission	Code *et al.* (1970)
1970	Atomic Hydrogen envelope mapping	Bertaux & Blamont (1970)
1971	*Water sublimation theory for comets*	Delsemme & Miller (1971)
1973	First detection of OH 18-cm lines (comet Kohoutek)	Biraud *et al.*, Turner (1974)
1973	First detection of HCN in a comet (Kououtek)	Huebner *et al.* (1974)
1982	1982–1987 International Halley Watch	Newburn & Rahe (1984)
1983	Discovery of S_2 with IUE (IRAS-Araki-Alcock)	A'Hearn *et al.*(1983)
1985	First detection of water in a comet (1P/Halley)	Mumma *et al.* (1986)
1986	First images of a cometary nucleus (1P/Halley)	Sagdeev *et al.* (1986a) Keller *et al.* (1986)
1986	Comet nuclei are dark (1P/Halley)	Sagdeev *et al.* (1986a)
1986	First measurement of D/H in water in a comet	Eberhardt *et al.* (1987)
1986	CHON particles detected in comet 1P/Halley	Kissel *et al.* (1987) Sagdeev *et al.* (1986b)
1986	Discovery of comet dust trails using IRAF	Sykes *et al.* (1986)
1986	*Interstellar model for comet nuclei*	Greenberg & Hage (1990)
1987	First polymer in space identified in comet Halley	Huebner (1987)
1987	Silicate emission in infrared spectra	Bregman *et al.* (1987)
1994	CO-driven activity in distant comet 29P	Senay & Jewitt (1994)
1994	Density and Structure of comet Shoemaker Levy 9	Asphaug & Benz (1996)
1995	Dichotomy carbon-rich/poor comets	A'Hearn *et al.*(1995)
1996	Discovery of X-ray & EUV emission from C/1996 B2	Lisse *et al.* (1996)
1997	Discovery of the Na tail	Cremonese *et al.*(1997)
2000	*Very low density of dust particles*	Fulle *et al.* (2000)
2000	A wealth of molecules discovered in C/1995 O1	Bockelée-Morvan *et al.* (2000)
2002	Origin of X-ray emission solved	Cravens (2002)
2002	The Christmas Tree	Biver *et al.* (2002)
2003	Anomalous nitrogen isotopic ratio in C/1995 O1	Arpigny *et al.* (2003)
2005	Ice on the surface of 9P/Tempel 1	Sunshine *et al.* (2006)
2006	First results of Stardust samples analysis	Brownlee *et al.* (2006)
2009	Glycine detected in Stardust samples	Elsila *et al.* (2009)
2011	103P/Hartley 2: A comet with Earth-like D/H	Hartogh *et al.* (2010)
2015	Detection of N_2 in comet 67P	Rubin *et al.* (2015)
2015	Detection of Argon in comet 67P	Balsiger *et al.* (2015)
2015	Detection of O_2 in comet 67P	Bieler *et al.* (2015)
2015	Images of dust aggregates in 67P dust coma	Schulz *et al.* (2015)

of knowledge. We also list in Table 6 the series of books published by the University of Arizona Press, which provide the state of knowledge at the time of their release. Several topical reviews have been published by the International Space Science Institute (ESA Publications), Space Science Reviews (Springer), and Astronomy and Astrophysics Reviews (e.g., Festou *et al.* 1993).

Table 8. Milestones in asteroid knowledge. Concepts and models are in italics.

Year	Highlight	Reference
1949	The Yerkes-McDonald survey of asteroids	Groeneveld & Kuiper (1954a,b)
1951	New asteroid families - Extending Hirayama findings	Brouwer (1951)
1956	Discovery of the opposition effect	Gehrels (1956)
1964	*In depth theory on the origin of meteorites in asteroids*	Anders (1964)
1967	*Mechanisms to deliver meteorites from the Main-Belt*	Wetherill (1967)
1968	First radar detection: (1566) Icarus	Goldstein (1968)
1969	*Collisional model of asteroids and their Debris*	Dohnanyi (1969)
1970	Polarimetry for measuring asteroid reflectivity	Veverka (1970)
1970	First IR diameter of an asteroid (Vesta)	Allen (1970)
1970	Asteroid in reflected light has composition implications	McCord *et al.* (1970)
1975	First asteroid classification	Chapman & Davis (1975)
1977	Vesta is the parent body of HEDs	Consolmagno & Drake (1977)
1979	Radar observation of (1) Ceres	Ostro *et al.* (1979)
1979	Stellar occultation of (6) Hebe	Dunham & Mallen (1979)
1980	*Asteroid impact caused Cretaceous-Tertiary extinction*	Alvarez *et al.* (1980)
1982	Compositional structure of the asteroid belt	Gradie & Tedesco (1982)
1983	Discovery of hydrated silicate on asteroid (2) Pallas	Larson *et al.* (1983)
1983	An asteroid as parent-body of the Geminid meteors	Whipple (1983)
1983	Asteroid photometric catalogue	Lagerkvist *et al.* (1983)
1984	Tholen asteroid taxonomy	Tholen (1984)
1990	Identification of asteroid families	Zappalà *et al.* (1990)
1993	First confirmation of collisional origin of a family	Binzel & Xu (1993)
1993	First detection of an asteroid binary (from space)	Chapman *et al.* (1995)
1994	NEOs as transient objects	Farinella *et al.* (1994)
1995	Asteroid orbit evolution due to Yarkovsky effect	Rubincam (1995)
1996	Space weathering solving the "S-type conundrum"	Chapman (1996)
1999	First detection of an asteroid binary (from ground)	Merline *et al.* (1999)
1999	Asteroid size distributions and families	Tanga *et al.* (1999)
1999	Bus taxonomy	Bus (1999)
2002	A low density for M-type (22) Kalliope	Margot *et al.* (2002)
2003	Detection of Yarkovsky effect	Chesley *et al.* (2003)
2005	Discovery of a multiple system (87) Sylvia	Marchis *et al.* (2005)
2005	Taxonomy of asteroids confirmed by polarimetry	Penttilä *et al.* (2005)
2006	Discovery of active asteroids in the Main Belt	Hsieh & Jewitt (2006)
2006	Low density of a Trojan binary	Marchis *et al.* (2006)
2007	Direct detection of the YORP effect	Lowry *et al.* (2007) Taylor *et al.* (2007)
2009	Bus-DeMeo taxonomy	DeMeo *et al.* (2009)
2010	Fresh surfaces on NEAs	Binzel *et al.* (2010)
2010	Detection of water ice on Themis	Campins *et al.* (2010) Rivkin & Emery (2010)
2010	Activity of Phaeton, parent of Geminid stream	Jewitt & Li (2010)
2011	First results from Hayabusa sample return	e.g., Nakamura *et al.* (2011)
2011	Spectral bimodality in Trojan swarms	Emery *et al.* (2011)
2011	*Grand Tack model*	Walsh *et al.* (2011)
2013	Detection of water vapor around Ceres	Kueppers *et al.* (2014)
2014	Compositional trends in asteroid belt	Demeo & Carry (2014)
2014	*Thermal fatigue responsible for regolith formation*	Delbo et al.(2014)

For this legacy report, we rather opted to select a few highlights that revolutionized or marked an important step towards our understanding of the physical and chemical properties of these bodies, with consequences on their formation, origin and evolution, and on the formation of the Solar System. Rather than reviewing in details these highlights,

Table 9. Milestones about trans-Neptunian objects and Centaurs. Concepts and models are in italics.

Year	Highlight	Reference
1943	*First prediction of a trans-Neptunian population*	Edgeworth (1943)
1951	*A primordial belt populated by comets beyond Pluto*	Kuiper (1951)
1977	Discovery of centaur (2060) Chiron	Kowal *et al.* (1979)
1978	Discovery of Pluto's satellite Charon	Christy & Harrington (1978)
1987	Pluton and Charon properties from mutual events	Tholen *et al.* (1987) Binzel (1988)
1988	Detection of Pluto's atmosphere from stellar occultation	Hubbard *et al.* (1988)
1990	Centaur Chiron is active	Luu & Jewitt (1990)
1992	Discovery of Kuiper-Belt object 1992 QB_1	Jewitt & Luu (1993)
1998	H_2O ice and organics on the surface of Pholus	Cruikshank *et al.* (1998)
2000	Extremely red Kuiper-Belt objects	Tegler & Romanishin (2000)
2001	Detection of a second trans-Neptunian binary 1998 WW_{31}	Veillet *et al.* (2001)
2003	Two distinct color populations of Centaurs	Peixinho *et al.* (2003)
2004	Crystalline ice/hydrated NH_3 detected on (50000) Quaoar	Jewitt & Luu(2004)
2005	Methane detected on dwarf planet Eris	Brown *et al.* (2005)
2007	Eris is more massive than Pluto	Brown & Schaller (2007)
2007	Discovery of a collisional family in the Kuiper-Belt	Brown *et al.* (2007)
2010	Successful stellar occultation by a TNO other than Pluto	Elliot *et al.* (2010)
2012	Large diversity of object albedos among classical TNOs	Vilenius *et al.* (2012)
2013	Density diversity in the Kuiper Belt	Brown *et al.* 2013
2014	Discovery of Chariklo's rings	Braga-Ribas *et al.* (2014)
2014	Color/albedo correlation in Kuiper-Belt objects	Lacerda *et al.* (2014)

we opted for providing a chronological list, starting from the early times of Commission 15. This synthetic approach provides an immediate overview of the important milestones in the field of Commission 15. Three separate tables are provided, focussing on comet, asteroid, or TNOs highlights (Tables 7, 8 and, 9; respectively), keeping in mind that the distinction between these objects is not sharp (Section 8), so that some highlights pertain to the whole population of small Solar System bodies.

8. The asteroid-comet-continuum

One of the major results of the research carried out in recent years has been a progressive change of paradigm for what concerns our understanding of the real differences between different classes of minor bodies that have been traditionally studied by separate scientific communities, in particular asteroids and comets.

It has always been clear that, in principle, it is not easy to distinguish between extinct comets and inactive bodies like the asteroids. This is particularly true for what concerns objects having experienced also a long dynamical evolution eventually leading them to become near-Earth objects. What has been increasingly evident in recent years, however, is that not only comets can become inactive and appear like asteroids, but also the opposite is true, in the sense that episodes of cometary-like activity have been observed in the case of some, apparently "normal" main belt asteroids (e.g., Hsieh *et al.* 2006, 2015). These bodies are now known as *main belt comets* or *active asteroids*. They are mostly located in the outer regions of the asteroid belt, where most asteroids belong to taxonomic classes characterized by low albedo and flat reflectance spectra, interpreted as features suggesting a primitive origin and poor thermal evolution since the epoch of their growth. That some asteroids present ices at their surface or in their interior has been directly evidenced by the detection of the infrared signature of ice on asteroids Themis (Campins *et al.* 2010, Rivkin & Emery, 2010) and Cybele (Licandro *et al.* 2011), and the detection of water vapour around Ceres (Kueppers *et al.* 2014).

The most recent models of the history of our planetary system support these ideas: the so-called Grand Tack model (Walsh *et al.* 2011) describes episodes of very early planetary migration followed by a stabilization of the Solar System, including a first epoch of intense dynamical and collisional evolution described by the so-called Nice model that applies at epochs close to the epoch of the Late Heavy Bombardment. They predict that the original population of planetesimals originally accreted at the heliocentric distance of the current asteroid belt was strongly perturbed and almost totally lost, whereas the region was later repopulated by planetesimals coming from both inner and outer regions. If this scenario is correct, the current asteroid belt can include, mainly in the outer regions, bodies that accreted in regions with high abundances of volatiles.

The distinction between comets and asteroids tends therefore to become increasingly blurred according to recent models. Moreover, in addition to the existence of main belt comets, there is also another piece of evidence coming from polarimetry. In particular, the so-called F-class, first introduced by Gradie and Tedesco (1982), includes objects that were later found to be likely of cometary origin, including the comet Wilson-Harrington, previously classified as the F-class asteroid 4015, and asteroid (3200) Phaeton, associated with the Geminid meteor shower. F-class asteroids are also characterized by distinctive polarimetric properties (in particular, a low inversion angle of linear polarization, see Belskaya *et al.* 2005). A comparison with polarimetric properties of a few cometary nuclei observed by Bagnulo *et al.* (2011) showed that the polarimetric behaviour of these objects exhibits noticeable similarities.

The convergence of observational evidence and of theoretical understanding leads us therefore to conclude that a strict separation of different classes of Solar System minor bodies is increasingly less justified than previously believed.

9. Report from 2012–2015 Task groups

9.1. *Asteroid Polarimetric Albedo Calibration*

The light that we receive from the asteroids at visible wavelengths is scattered sunlight, and is therefore in a state of partial linear polarization. The first extensive applications of polarimetric techniques to the study of asteroids date back to the 70s. Fundamental pioneering studies were carried out by some authors, including B. Zellner, A. Dollfus, T. Gehrels, J. Gradie. The main results were summarized in the book *Planets, Stars and Nebulae Studied with Photopolarimetry*, edited by T. Gehrels in 1974. At that time it was already evident the importance of polarimetry as a technique to derive information about the geometric albedo and on the properties of the regolith covering the surfaces of atmosphereless Solar System bodies. In the following decades further observational activities carried out by a few research teams in the US and in Europe (mainly in Ukraine) led to the discovery of the rotational modulation of the fraction of linear polarization of the asteroid (4) Vesta, and to better calibrations of some relations between the geometric albedo and some polarization properties, based on empirical evidence. On the theoretical side, the progress was relatively slow, until the 90s, when the importance of the so-called Coherent Backscattering Mechanism was fundamental to start to interpret results of remote observations and laboratory experiments in the framework of a credible theoretical scenario.

Starting from the mid-90s, after some years of slow progress due to poor availability of dedicated instruments, and to the problems posed by a technique requiring several measurements per object over a variety of observing circumstances, asteroid polarimetry has started to experience a period of real renaissance also on the side of observational activities, when some new research teams, mainly in Argentina and Italy, and later also in other European countries (France, UK) started to collaborate in the field. The current state-of-the-art is described in the Belskaya *et al.* chapter in the Asteroids IV book, and in some chapters in the book Polarimetry of Stars and Planetary Systems, edited in 2015 by Kolokolova, Hough and Levasseur-Regourd (Cambridge University Press).

A brief list of achievements obtained in recent years includes:

- A much better calibration of different albedo - polarization relations involving a number of parameters describing the observed variation of linear polarization as a function of varying solar phase angle (the angle between the Sun and the observer, as seen by the target object). According to the most recent analyzes, it seems that albedos obtained from polarization data are much more reliable than those derived from thermal radiometry observations, the latter having been so far the most important sources of albedo data.
- The study of the differences in polarimetric behaviour exhibited by asteroids belonging to different taxonomic classes, including a possible link between objects belonging to the asteroid F class and comets.
- The discovery of the so-called Barbarian asteroids, so named after the prototype of this class, asteroid (234) Barbara, whose unusual polarimetric behaviour was first discovered by Cellino *et al.* (2006). According to current knowledge, based also on the availability of the reflectance spectra for some Barbarians, these objects may be the remnants of the very first generation of planetesimals accreted in the early Solar System (Cellino *et al.*, 2014).
- The recognition, based on some first pioneering analyzes (Bagnulo *et al.*, 2015), that spectro-polarimetry, merging together reflectance spectroscopy and polarimetry, may become in the years to come a major tool to obtain a reliable physical characterization of the asteroids.
- The application of polarimetry to the physical characterization of potentially hazardous objects, the first example having been that of (99942) Apophis, observed at ESO VLT (Delbo *et al.*, 2007).

The development of new and better instruments, and the interest of increasing numbers of research teams in different countries, promises to sustain and strengthen the current research activities in asteroid polarimetry, and to continue the progress experienced in recent years.

9.2. *The H,G_1,G_2 Magnitude System*

In the three-parameter H, G_1, G_2 magnitude phase function for asteroids, the reduced observed magnitudes $V(\alpha)$ (α is the solar phase angle) can be obtained from (Muinonen et al. 2010; see also Penttilä *et al.* 2016 and Shevchenko *et al.* 2016)

$$\begin{aligned} 10^{-0.4V(\alpha)} &= a_1\Phi_1(\alpha)+a_2\Phi_2(\alpha)+a_3\Phi_3(\alpha) \\ &= 10^{-0.4H}[G_1\Phi_1(\alpha)+G_2\Phi_2(\alpha)+(1-G_1-G_2)\Phi_3(\alpha)], \end{aligned} \qquad (9.1)$$

where the basis functions Φ_1, Φ_2, and Φ_3 are given in Tables 10 and 11. In particular, $\Phi_1(0)=\Phi_2(0)=\Phi_3(0)=1$. The absolute magnitude H and the coefficients G_1 and G_2 are

$$H = -2.5\log_{10}(a_1+a_2+a_3),$$

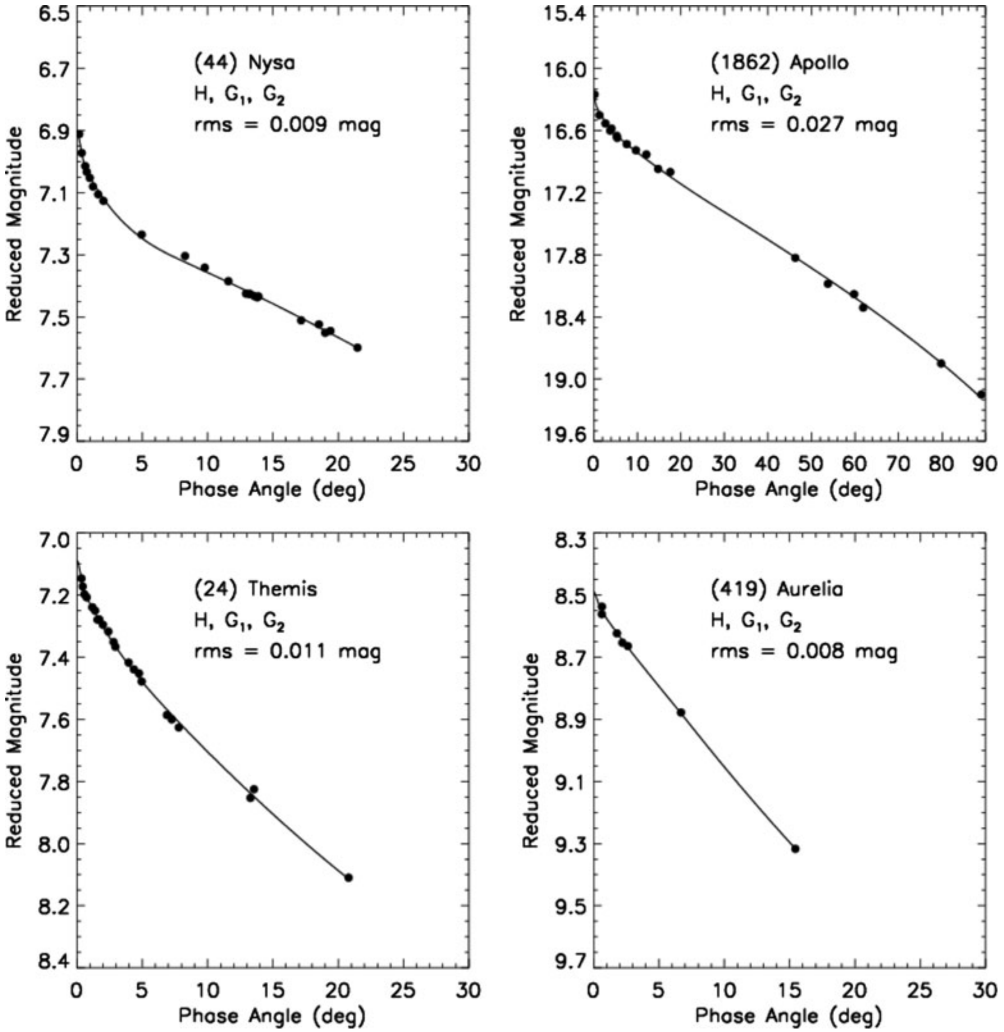


Figure 6. Linear least-squares fits (solid lines) to the phase curves of the E-class asteroid (44) Nysa (top left; observations by Harris *et al.* 1989a), the Q-class near-Earth object (1862) Apollo (top right; Harris *et al.* 1987), the C-class asteroid (24) Themis (bottom left; Harris *et al.* 1989b), and the F-class asteroid (419) Aurelia (bottom right; Harris and Young 1988) using the H, G_1, G_2 magnitude phase functions.

$$\begin{aligned} G_1 &= \frac{a_1}{a_1 + a_2 + a_3}, \\ G_2 &= \frac{a_2}{a_1 + a_2 + a_3}. \end{aligned} \tag{9.2}$$

The coefficients a_1, a_2, and a_3 are estimated from the observations by using the linear least-squares method. Thereafter, H, G_1, and G_2 follow from the nonlinear relations in Eq. 9.2. The H,G_1,G_2 system has been developed by a team of researchers led by Dr. Alberto Cellino convening twice at the International Space Science Institute in Bern, Switzerland in 2008, with their findings documented in Muinonen *et al.* (2010).

At the IAU General Assembly in Beijing, 2012, the novel three-parameter H,G_1,G_2 magnitude system was introduced as a replacement for the earlier two-parameter H,G magnitude system (Bowell *et al.* 1989). Furthermore, the H,G_1,G_2 system was

Table 10. The basis functions Φ_1 and Φ_2 of the H, G_1, G_2 magnitude phase function. Φ_1 and Φ_2 are linear for $\alpha \leqslant 7.5°$: $\Phi_1(\alpha) = 1 - \frac{6\alpha}{\pi}$ and $\Phi_2(\alpha) = 1 - \frac{9\alpha}{5\pi}$. Values for larger phase angles follow from cubic splines passing through the tabulated points with the requirement that the first derivatives are $\Phi_1'(\frac{\pi}{24}) = -\frac{6}{\pi}$, $\Phi_2'(\frac{\pi}{24}) = -\frac{9}{5\pi}$, $\Phi_1'(\frac{5\pi}{6}) = -9.1328612 \times 10^{-2}$, and $\Phi_2'(\frac{5\pi}{6}) = -8.6573138 \times 10^{-8}$.

α (°)	Φ_1	Φ_2
7.5	7.5×10^{-1}	9.25×10^{-1}
30.0	3.3486016×10^{-1}	6.2884169×10^{-1}
60.0	1.3410560×10^{-1}	3.1755495×10^{-1}
90.0	5.1104756×10^{-2}	1.2716367×10^{-1}
120.0	2.1465687×10^{-2}	2.2373903×10^{-2}
150.0	3.6396989×10^{-3}	1.6505689×10^{-4}

Table 11. The basis function Φ_3 of the H, G_1, G_2 phase function. Values at intermediate phase angles follow from cubic splines passing through the tabulated points with the requirement that the first derivatives are $\Phi_3'(0) = -1.0630097 \times 10^{-1}$ and $\Phi_3'(\frac{\pi}{6}) = 0$.

α (°)	Φ_3
0.0	1
0.3	8.3381185×10^{-1}
1.0	5.7735424×10^{-1}
2.0	4.2144772×10^{-1}
4.0	2.3174230×10^{-1}
8.0	1.0348178×10^{-1}
12.0	6.1733473×10^{-2}
20.0	1.6107006×10^{-2}
30.0	0

complemented by a nonlinear least-squares H,G_{12} system to be utilized in the cases of scarce photometric data. The H,G_1,G_2 system was unanimously accepted, first, at the Business Meeting of IAU Commission 15 on August 29, 2012, and, second, at the Business Meeting of IAU Division III on August 30, 2012. Whereas the H,G system had been performing in a satisfactory way for the vast majority of asteroids studied, it had been frequently facing difficulties in the cases of dark asteroids with no opposition effects and bright asteroids with narrow and pronounced opposition effects. These difficulties were arising due to the coherent-backscattering mechanism (CBM; Li *et al.* 2016, and references therein) that, towards the end of 1980s, was understood to be responsible, at least partially, for the opposition effects of asteroids. The CBM is a multiple-scattering interference mechanism: multiply scattering waves propagating in opposite directions along the same geometric paths in complex random media (like the surfaces of asteroids) always interfere constructively at backscattering (in the opposition geometry) but not necessarily in other directions.

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Dominique Bockelée-Morvan
President of the Commission

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