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Commission 20: Positions and Motions of Minor Planets, Comets and Satellites

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1. Introduction

The past triennium has continued to see a huge influx of astrometric positions of small solar system bodies provided by near-Earth object (NEO) surveys. As a result, the size of the orbital databases of all populations of small solar system bodies continues to increase dramatically, and this in turn allows finer and finer analyses of the types of motion in various regions of the orbital elements space.

The detection of impact possibilities in the next decades, an activity that started in 1999, has currently reached routine status, and is carried out in several centres: NEODyS (in Pisa, Italy, `http://newton.dm.unipi.it/cgi-bin/neodys/neoibo` and Valladolid, Spain, `http://unicorn.eis.uva.es/cgi-bin/neodys/neoibo`), and Sentry (in Pasadena, CA, USA, `http://neo.jpl.nasa.gov/risk/`) (Milani *et al.* 2005, Icarus 173, 362).

This activity has led to the detection of the exceptionally close encounter with the Earth of NEA (99942) Apophis, a 19^{th} magnitude object, discovered in 2004, that will pass within the geostationary satellites ring on 13 April 2029. As a result of the encounter, the orbit of Apophis will be transferred from the Aten to the Apollo class, and a resonant return (Valsecchi *et al.* 2003, A&A 408, 1179) to collision with the Earth in 2036 is still allowed by the currently available astrometry, although its probability is low. There will be many opportunities in the coming years to refine the orbit, also through radar observations, and anyway an orbital deflection, if needed, appears to be quite feasible, according to ongoing studies carried out by ESA and NASA.

In the near future, the start of operations of next generation NEO surveys like, for example, Pan-STARRS, is likely to further increase by a couple of orders of magnitude the currently available astrometric and orbital databases, with consequences on the development of our knowledge of the motions of small solar system bodies that are not easy to imagine.

2. Meetings

The following meetings, held in the triennium covered by this report, were of relevance to the work of Commission 20:

- Asteroids, Comets, Meteors 2002, 29 July–2 August 2002, Berlin, Germany;
- Scientific Requirements for Mitigation of Comets and Asteroids, 3–6 September 2002, Washington, DC, USA;

• Planetary Defense Conference: Protecting Earth from Asteroids, 23–26 February 2004, Garden Grove, CA, USA;

• IAU Colloquium 197: Dynamics of Populations of Planetary Systems, 31 August–4 September 2004, Belgrade, Serbia and Montenegro.

3. Asteroids (A. Lemaître)

The major event of the last three years for the asteroid belt is the fantastic and exponentially increasing number of data, and it is only the beginning of this phenomenon.

Very large catalogues of asteroids are now available, not only in osculating elements, but also in proper elements: a systematic calculation of the proper elements has been developed by Knežević and Milani (2003, A&A 403, 1165); it consists of a purely numerical procedure, based on time integrations over periods of 2 Myr (10 Myr for some cases) with complete catalogues regrouping more than 100 000 asteroids, with analytical and synthetic proper elements.

Many more data concerning lightcurves of asteroids are now available, due to systematic surveys of specific regions of the sky. Let us mention especially the Sloan Digital Sky Survey Moving Object Catalog (SDSS MOC, Stoughton *et al.* 2002, AJ 123, 485), with more than 125 000 objects, and the Small Belt Asteroid Spectroscopy Survey II (SMASS II, Bus and Binzel 2002, Icarus 158, 106). Based on the SMASS survey and the intensive use of CCD cameras, a new taxonomy was recently proposed by (Bus and Binzel 2002, Icarus 158, 146) based on 1447 asteroids. The result gives 26 classes of planets, in which new subdivisions of the classes C, S, X appear with respect to the basic taxonomy of Tholen. This taxonomy has been adopted by other groups, as shown by the results of Carvano *et al.* (2003, Icarus, 161, 356) and Mothé-Diniz *et al.* (2003, Icarus 162, 10) .

Systematic observations of the sky are at the origin of the discovery of hundreds of thousands of new objects, near Earth, main belt, Jupiter's Trojans (the number of identified objects orbiting about L_4 is now over 1100, and about L_5 over 700) or transneptunians (over 900; see the lists at `http://cfa-www.harvard.edu/iau/lists/Unusual.html`).

Many of the theories usually accepted for the objects of the main belt have been tested with a few hundreds objects during the last decades; they have to be checked and reviewed nowadays with a much more statistically significant data set.

The definition of a family, for example, as given in the glossary of Asteroids III in 2002, still corresponded to a static and sequential approach to the phenomenon. It has now been shown that nongravitational forces (the thermal Yarkovsky force in particular) and resonances (even the three-body ones) both affect the stability of the proper elements and have to be taken into account in the mechanisms of formation to reproduce the real families.

Indeed, the Yarkovsky effect introduces a kind of random walk, pushing the objects in or close to the resonances; it allows family mambers to diffuse in proper elements space, giving a nonuniform spreading shape to the cluster(Nesvorný *et al.* 2002, Icarus 157, 155; Carruba *et al.* 2003, Icarus, 162, 308; Tsiganis *et al.* 2003 Icarus 166, 131).

For the first time and thanks to this new dynamical approach, it was shown, by backwards integrations, that 13 members of a potential family converged to a single orbit, assumed to be that of the pre-breakup parent object, 5.8 Myr (±0.2 Myr) ago (Nesvorný *et al.* 2002, Nature 417, 720).

Let us mention that the Yarkovky effect was measured for the first time thanks to several radar observations of the NEA (6489) Golevka. A shift of 15 km in the asteroid position was clearly detected on this period of 12 years by Chesley *et al.* (2003, Science 302, 1739).

The increasing number of asteroids discovered in the main belt has confirmed the reality of the 19 or 20 big families, identified in the nineties; they are much larger than before and they respect the laws of sizes expected for fragments (Holsapple *et al.* 2002, in Asteroids III, p. 443). New families also appeared, using the extended database of proper elements, but only after that a new idea was introduced by Nesvorný *et al.* (2004, Icarus 173, 132): the "distance" between two objects in the cluster should be a function both of the dynamical proper elements and of the taxonomic components (coming from new surveys and large catalogues). In a sample of 106 284 minor planets about 40 families were clearly identified (the basic ones and the so called "micro" ones), regrouping 38 625 asteroids (about 36% of the whole population).

There are still open issues concerning asteroid families; these are reviewed by Cellino *et al.* (2004, Planet. Space Sci. 52, 1075).

Numerical simulations of collisions and disruptions were performed by Michel *et al.* (2003, Nature 421, 608), using sophisticated numerical algorithms from fluid dynamics.

Many of the catastrophic events at the origin of the breakup of a family can now be dated by different techniques (see Dell'Oro *et al.* 2004, Icarus 169, 341, and Knežević and Pavlović 2002, EMP 88, 155) and, surprisingly, some of the families turn out to be very young (less than 1 Myr).

The age of the families has a very important consequence: it allows to measure the traces of space weathering (i.e., of all the processes that alter the optical properties of surfaces of airless bodies), by comparative study of the surfaces of members of old and young families. It is now recognized that an age dependent component alters asteroid colors (Chapman 2004, Ann. Rev. Earth & Planet. Sci. 32, 539).

The dynamics of asteroids has been refined due to results obtained for exoplanets, where similar cases of resonances have been analyzed; the main contributions are local, like for the Trojans using diffusion mechanism (Tsiganis *et al.* 2005, Icarus 166, 131) or for the Hilda resonant group (Miloni *et al.* 2004, CeMDA. 92, 89).

The observation of asteroids by radar, for the closest, and by several adaptative optics surveys, for the main belt, has revealed an important presence of binaries in all the populations (Margot 2004, Bull. Amer. Astron. Soc. 36, 12.02): near-Earth, main belt and trans-Neptunian populations. Recently, asteroid (87) Sylvia was clearly identified as a triple asteroid by Marchis *et al.* (2003, Nature 436, 822). A detailed study of the orbit of the satellite of (22) Kalliope was carried out by Marchis *et al.* (2003, Icarus 165, 112), while the problem of the stability of binary asteroids wass addressed by Scheeres (2002, Icarus 159, 271). the formation of asteroid satellites in large impacts was simulated numerically by Durda *et al.* (2004, Icarus 170, 243).

Another important challenge to mention is the crucial need for detailed models of asteroids: the determination of the object shape, of its rotational rate and of the scattering properties of its surface, from radar measurement, and also from light curves has made considerable progress (Cellino *et al.* 2003, Icarus 162, 278).

4. Comets (J.A. Fernández)

Comet dynamics in the last triennum has advanced in some specific issues, among which we can mention:

Fernández *et al.* (2002, Icarus 159, 358) have analyzed the dynamical evolution of Jupiter family comets and near-Earth asteroids with aphelion distances $Q > 3.5$ AU, paying special attention to the mixing of both populations in such a way that inactive comets may be masqueraded as asteroids. The population of NEAs with smaller aphelion distances is found to be a suitable source of NEAs in cometary orbits, which allows to set an upper limit of ~20 % to the putative component of deactivated JF comets among asteroids.

New models for computing the action of the tidal force of the galactic disk on Oort cloud comets were developed by Fouchard (2004, MNRAS 349, 347) based on the Hamiltonian form of the equations of motion averaged over the mean anomaly, and a series of mappings of different orders. The author found that the radial component of the galactic tide has a non-negligible dynamical effect on the injection of Oort cloud comets in the inner planetary region.

Matese and Lissauer (2004, Icarus 170, 508) have presented a statistical test to show that the tidal field of the galactic disk controls the injection rate of Oort cloud comets in the inner planetary region. The test measures the greater likelihood that an Oort cloud comet has decreased its angular momentum (and thus its perihelion distance) during the last orbital revolution than the other way around.

From numerical simulations of scattered disk objects (SDOs), Fernández *et al.* (2004, Icarus 172, 372) have found that nearly 50% of the SDOs are transferred to the Oort cloud, from which about 60% have their perihelia beyond Neptune's orbit ($31 < q < 36$ AU) at the moment of reaching the Oort cloud. This shows that Neptune acts as a dynamical barrier that scatters most of the bodies to near-parabolic orbits before they can approach or cross Neptune's orbit in non-resonant orbits. The authors found that the current rate of SDOs with radii $R > 1$ km incorporated into the Oort cloud is about 5 yr^{-1}, which might be a non-negligible fraction of comet losses from the Oort cloud (probably around or even above 10%).

Morbidelli and Levison (2004, AJ 128, 2564) have discussed different mechanisms for producing high-eccentricity and high-perihelion distance objects in the trans-Neptunian region, like 2000 CR_{105} and (90377) 2003 VB_{12} (Sedna). The mechanisms analyzed were: (i) the passage of Neptune through a high-eccentricity phase, (ii) the past existence of massive planetary embryos in the trans-neptunian belt or the scattered disk, (iii) the presence of a massive trans-neptunian disk at early epochs which exerted tides on scattered disk objects, and (iv) encounters with nearby stars. They conclude that the only mechanism that explains satisfactorily the existence of such objects is the star passage. In agreement with this conclusion, Rickman *et al.* (2004, A&A 428, 673) have also found from Monte Carlo simulations that Sedna-like objects would form during stellar encounters.

Gomes *et al.* (2005, CeMDA 91, 109) found that the Kozai mechanism associated with a mean motion resonance is the main responsible for raising both the perihelia and the inclination of scattered disk objects. The highest perihelion distance found was about 70 AU. This mechanism may explain the existence of most high-perihelion SDOs, though the authors argue that Sedna with $q \sim 76$ AU could as well belong to the inner core of the Oort cloud.

Gomes *et al.* (2005, Nature 435, 466) have proposed that the late heavy bombardment on the terrestrial planets was triggered by the rapid migration of the accreting Jupiter and Saturn which led them to cross their mutual 1:2 mean motion resonance. When this occurred their orbits became eccentric, thus destabilizing the orbits of Uranus and Neptune. These two planets then moved out interacting with an outer planetesimal disk. The process took altogether about 700 Myr. According to the authors, the scattered planetesimals caused the late heavy bombardment.

5. Satellites (J.E. Arlot)

5.1. *Activities of the Working Group on Natural Planetary Satellites (J.E. Arlot, chairman)*

The activities of the working group on Natural planetary satellites were mainly dedicated to the maintenance of the data base of astrometric observations of the natural planetary satellites:

• mutual events of the galilean satellites: most of the events observed during the past campaigns are available; the lightcurves are available for 1985, 1991 and 1997;

• astrometric observations: most of the observations made in the countries of the former Soviet Union before 1990 are now available and old data are under scanning to be added to the data base which has been presented by Emelianov and Arlot at the American Astronomical Society, DPS meeting #37, #47.06;

• bibliographic data: all the astrometric data are documented through the data base of the papers where they were published. Theoretical papers are also included in the database.

An effort has been made to use the best dynamical theories to build ephemerides for use by the observers of the natural planetary satellites.

The site of the working group is available at: `http://www.imcce.fr/iauwg`; the data base is available at: `http://www.imcce.fr/nsdc`.

5.2. *Astrometric observations performed during the triennum 2002–2005*

Numerous discoveries were made thanks to large telescopes exploring the sky where new faint satellites may be found. The known satellites were observed either from ground-based telescopes, or from space in order to maintain the quality of the dynamical models of their motions.

5.2.1. *Discovery of new satellites*

Many new outer satellites of the giant planets were discovered during the past triennum such as S/2001 U 3 (Marsden *et al.* 2003), S/2001 U2 and S/2002 N4 (Holman *et al.* 2003), S/2001 U1 (Holman *et al.* 2002), S/2002 J1 (Sheppard *et al.* 2002), S/2003 J22 (Sheppard *et al.* 2004), S/2003 J19 and S/2003 J20 (Gladman *et al.* 2003), S/2003 J8 (Sheppard *et al.* 2003), S/2003 U3 (Sheppard *et al.* 2003), S/2003 U1 and S/2003 U2 (Showalter *et al.* 2003), S/2005 S1 (Porco, 2005. Other new satellites of Saturn were announced by Sheppard *et al.* (2005) and by Jewitt *et al.* (2005). A Survey for Outer Satellites of Mars and determination of the Limits to Completeness was made by Sheppard *et al.* in AJ, 128, 2542 (2005).

5.2.2. *Observations of known satellites*

Mutual events and phenomena of the galilean satellites observed in 1997 and 2003 were published by Dourneau *et al.* in A&A 437, 711 (Bordeaux Observatory, France), by Pauwels *et al.* in A&A 437, 705 (Uccle-Bruxelles Observatory, Belgium), by Loader in New-Zealand (2004) and by Vienne *et al.* at Lille Observatory, France (2003).

U.S. Naval Observatory (USA): using Hubble Space Telescope Astrometric Observations, Pascu *et al.* made Orbital Mean Motion Corrections for the Inner Satellites of Neptune in AJ 127, 2988. Upgrades to the Flagstaff Astrometric Scanning Transit Telescope were made by Stone *et al.* in AJ 126, 2060.

China: astrometry is under development in China as shown by Jin Weng-Jing *et al.* (2004) and 1997–2000 CCD astrometric observations of Saturn's satellites and comparison with theories have been published by Qiao *et al.* in A&A 422, 377 (2004).

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Institut de mecanique celeste (Paris, France): CCD observations of Phoebe have been published by Fienga *et al.* in A&A 391, 767 (2002).

Ukraine: astrometric CCD observations of the inner Jovian satellites in 1999–2000 were published by Kulyk *et al.* in A&A 383, 724 (2002).

Minor Planet Center, Cambridge (USA): ahe Minor Planet Center has concerned itself with announcing new discoveries of planetary satellites (in collaboration with CBAT, which is responsible for assigning designations to new discoveries), determining preliminary orbits, publishing follow-up astrometry and updating orbits as necessary and disseminating observational and orbital information via the MPECs and Minor Planet Circulars.

Rio de Janeiro Observatory, CNPq, (Brazil): many sets of observations were published: CCD astrometric observations of Amalthea and Thebe by Veiga and Vieira Martins in A&A 437, 1147 (2005); CCD astrometric observations of Saturnian satellites by Veiga *et al.* in A&A 400, 1095 (2003); Positions of Uranus and Its Main Satellites by Veiga *et al.* in AJ, 125, 2714; Systematic astrometric observations of Proteus by Vieira Martins *et al.* in A&A 425 1107 (2004).

JPL, Pasadena (USA): a paper on Groundbased Radar Investigations of Asteroids and Planetary Satellites was published by Ostro in AJ 123, 1776.

Observations from Space: solar eclipses of Phobos and Deimos were observed from the surface of Mars and published by Bell *et al.* in Nature 436, 55 (2005). A paper on the possible observation of the Natural Satellites of Solar System Bodies with Gaia was published by Tanga and Mignard in the Proceedings of the Gaia Symposium "The Three-Dimensional Universe with Gaia" (ESA SP-576). Jovian satellite positions from Hubble Space Telescope images were published by Mallama *et al.* in Icarus 167,320.

5.3. *Processing of observations*

The processing and re-processing of existing observations allowed to get new data very useful for dynamical purpose.

U.S. Naval Observatory, Washington D.C. (USA): from scanning of the large USNO photographic plates archive new observations were deduced from unmeasured plates by Pascu *et al.* (2005).

Institut de mecanique celeste (Paris, France) and IIA, Bangalore (India): observation and reduction of mutual events in the solar system were published by Noyelles *et al.* in the Proceedings of IAU Colloquium #196, held 7–11 June, 2004 in Preston, U.K. and Astrometry from CCD photometry of mutual events of Jovian satellites from VBO during 1997 were published by Vasundhara in A&A 389,325 (2002). Astrometry from mutual events of Jovian satellites in 1997 were published by Vasundhara *et al.* in A&A 410, 337 (2003).

China: image-processing techniques in precisely measuring positions of Jupiter and its Galilean satellites were published by Peng *et al.* in A&A 401, 773 (2003) and new confirmation of image-processing techniques for astrometry of Saturn and its satellites by Peng in MNRAS, 359, 1597.

5.4. *Ephemerides*

Ephemerides of the natural planetary satellites are available through Internet on the JPL site, the IMCCE and SAI sites and, for the outer satellites of the giant planets, on the MPC site.

Sternberg Astronomical Institute SAI (Moscow, Russia): ephemerides of the outer Jovian satellites were published by Emelyanov in A&A 435, 1173.

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Minor Planet Center, Cambridge (USA): ephemerides of the outer satellites of the giant planets are continuously produced at the MPC and provided through Internet.

Institut de mecanique celeste IMCCE (Paris, France): the mutual events of the Galilean Satellites of Jupiter for 2002–2003 were calculated by Arlot (2002) and are available through Internet together with an interactive software allowing the calculation of the local observational conditions. The mutual events including Amalthea were also published by Vachier *et al.* in A&A 394, L19 (2002). Concerning the Galilean satellites, ephemerides were published thanks to a brand new theory by Lainey *et al.* in A&A 427, 371 (2004).

IMCCE (Paris, France) and SAI (Moscow, Russia): ephemerides of all the natural planetary satellites are available through Internet on the web servers of IMCCE and SAI.

5.5. *Theoretical work*

Theoretical works were of two kinds: either developments allowing to make ephemerides or analysis of the evolution of the dynamics of some satellite system.

Theoretical works were continued on the motion of the satellites systems and we will note the following works: Saturn's moon Phoebe as a captured body from the outer Solar was published by Johnson and Lunine in Nature 435, 69 (2005). Cuk and Gladman published a paper on the constraints on the orbital evolution of Triton in ApJ 626, L113. Numerical simulations of the orbits of the Galilean satellites were performed by Musotto *et al.* and published in Icarus 159, 500. A collisional origin of families of irregular satellites was studied by Nesvorn *et al.* and published in AJ 127, 1768. Nesvorn *et al.* also published a paper on the orbital and collisional evolution of the irregular satellites in AJ 126, 398. The orbital evolution of the distant satellites of the giant planets was studied by Vashkov'yak and Teslenko (Astronomy Letters 31, 140, 2005).

JPL, Pasadena, USA: a paper on the orbits of the major Saturnian satellites and the gravity field of Saturn from spacecraft and Earth-based observations was published by Jacobson in AJ 128, 492. The origin of chaos in the Prometheus-Pandora system was studied by Goldreich and Rappaport in Icarus 166, 320. Jacobson and Owen published a paper on the orbits of the inner Neptunian satellites from Voyager, Earth-based, and Hubble Space Telescope observations in AJ 128, 1412.

Cornell University, USA: chaos and the effects of planetary migration on the orbit of S/2000 S5 Kiviuq were studied by Carruba *et al.* in AJ 128, 1899 and a paper on the inclination distribution of the Jovian irregular satellites was published by Carruba *et al.* in Icarus 158, 434.

Queen Mary, University of London, UK: the dynamical influences on the orbits of Prometheus and Pandora were studied by Cooper and Murray in AJ 127, 1204.

Torun Centre for Astronomy, N. Copernicus University, Poland: an analytical theory of the motion of Phobos and a comparison with numerical integration were studied in A&A 416, 1187 (2004).

Goddard NASA Center, USA: free and forced obliquities of the Galilean satellites of Jupiter were studied by Bills in Icarus 175, 233.

Sternberg Astronomical Institute (Moscow, Russia): the mass of Himalia from the perturbations on other satellites was determined by Emelyanov in A&A 438, L33 and the dynamics of planetary satellites in the solar system were studied by Ural'skaya in Solar System Research 37, 337 (2003).

Institut de mecanique celeste (Paris, France): a brand new theory of the motion of the Galilean satellites of Jupiter was made thanks to frequency analysis by Lainey *et al.* and published in A&A 420, 1171 (2004) and and will be applied to make new ephemerides after fit to the available observations (Lainey and Vienne 2001, in Colloq. CELMECIII, Rome, Italy). The masses and orbital positions of Prometheus and Pandora during the Cassini tour were published by Renner *et al.* in Icarus 174, 230.

University N-D de la Paix, Namur, Belgium: the rotation of Europa was studied by Henrard and published in Celestial Mechanics and Dynamical Astronomy, 91, 131, using a semi-analytical theory of the rotation of Europa the Galilean satellite of Jupiter. The theory is semi-analytical in the sense that it is based on a synthetic theory of the orbit of Europa developed by Lainey. The theory is developed in the framework of Hamiltonian mechanics, using Andoyer variables and assumes that Europa is a rigid body. It is a first step toward the modelization of a non rigid Europa covered by an ocean.

Universidade Estadual Paulista, Brazil: a study on the dynamics of some resonances of Phobos in the future was published by Yokoyama *et al.* in A&A 429, 731 (2005). Yokoyama *et al.* published also a study fn the orbits of the outer satellites of Jupiter in A&A 401, 763 (2003).

China: a Re-determination of Phoebe's orbit was made by Shen *et al.* and published in A&A 437, 1109 (2005).

5.6. *Satellites of asteroids*

Very few astrometric positions are available for the fit of a dynamical model for any discovered satellite of asteroid and an effort is to be made to gather these data for dynamical purpose. Publications are, most often, made in order to present discoveries.

A probable detection of a moon of asteroid 98 Ianthe and a moon of asteroid 1024 Hale was published by Venable in Occultation Newsletter, (IOTA) 11, 5 and 8 (2004). A paper by Ryan *et al.* is entitled 3782 Celle: Discovery of a binary system within the Vesta family of asteroids and was published in Planet. Space Sci. 52, 1093. IAU Circ. 8232, 2 (2003) announced the discovery of S/2003 (22899) 1 by Merline *et al.* and IAU Circ. 7980, 2 (2002), also by Merline *et al.* announced the discovery of S/2002 (121) 1.

5.7. *Rings*

Most of the publications concerning the rings are dedicated to planetology and few deal with the dynamics of the particles of the rings.

Local n-body simulations for the rotation rates of particles in planetary rings were published by Ohtsuki and Toyama in AJ 130, 1302. Three-dimensional dynamics of narrow planetary rings were published by Chiang and Culter in ApJ 599, 675. A paper on the stability of Saturn's rings to gravity disturbances was published by Griv *et al.* in A&A 400, 375 (2003).