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Commission 16: Physical Study of Planets and Satellites

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Abstract. This report is a brief summary of some of the major achievements in studies of planets and satellites that have been accomplished during the years 2003–2005. Unlike previous years, we do not attempt to provide a detailed overview of the field but rather choose to highlight aspects which are of particular novelty.

Keywords. Io, Jupiter, Mars, Mercury, Moon, Neptune, satellites, Saturn, Titan, Uranus

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1. New Planets?

(Contributed by G. Consolmagno, Vatican Observatory, Vatican City State)

The discovery of a number of objects in the outer solar system with sizes that rival or exceed Pluto (Brown, Bouchez, Rabinowitz, *et al.* (2005a); Brown, Trujillo, Rabinowitz, *et al.* (2005b)) has reopened the debate on the nature and definition of a planet. If one counts these as new planets, their discovery would represent one of the most fundamental advances in planetary sciences of the past three years. The status of these bodies is the subject of a special IAU Working Group on the Definition of a Planet, which will provide a report elsewhere. As of this writing, no consensus definition is in sight, and indeed any such definition will inevitably be open to further review and debate as new data on the inventory of the outer solar system progresses.

2. Spacecraft Missions

(Contributed by G. Consolmagno, Vatican Observatory, Vatican City State; M. Roos-Serote, Lisbon Astronomical Observatory, Portugal)

Undoubtedly, among the more spectacular advances in the study of planets and satellites over the past three years have been the result of numerous successful spacecraft missions. The table lists the planetary mission activity in the 2003–2005 time frame. Preparations are well underway for further missions to Mercury, Venus and Pluto, along with follow-on missions to Mars.

The results of these spacecraft are far too numerous to detail here. New results for the previous triennium are the subject of a Joint Discussion held at the 2006 General Assembly, and can be found in the proceedings of that meeting.

Table 1. Spacecraft Missions to the Solar System, 2003–2005

Mission	Planet	Arrival	Status	Agency
Beagle2	Mars (surface)	25-12-2003	failure	BNSC, ESA
Cassini/Huygens	Saturn System	30-06-2004	operating	NASA, ESA, ASI
Deep Impact	Comet Temple-1	04-07-2005	completed	NASA
Huygens	Titan (surface)	14-01-2005	completed	ESA, NASA, ASI
Galileo	Jupiter	07-12-1995	completed	NASA
2001 Mars Odyssey	Mars	24-10-2001	operating	NASA
Mars Exploration Rover/Spirit	Mars (surface)	03-01-2004	operating	NASA
Mars Exploration Rover/Opportunity	Mars (surface)	24-01-2004	operating	NASA
Mars Express	Mars	25-12-2003	operating	ESA
Mars Global Surveyor	Mars	11-09-1997	operating	NASA
Mars Reconnaissance Orbiter	Mars	03-2006	en route	NASA
Nozomi	Mars	12-2003	failure	JAXA
Rosetta	Comet 67 P/Churyumov-Gerasimenko	05-2014	en route	ESA
Rosetta Lander	Comet 67 P/Churyumov-Gerasimenko	05-2014	en route	Philea
SMART-1	Moon	19-11-2004	operating	ESA
Stardust	Comet Wild-2 (tail)	02-01-2004	en route (back)	NASA

3. Mars

(Contributed by M. Roos-Serote, Lisbon Astronomical Observatory, Portugal)

Many new results have been obtained by ground-based telescopes and modeling that complement the tremendous amount of data being sent back by the several orbiting spacecraft and the two Mars Exploration Rovers.

Among the most intriguing discoveries in the atmosphere has been the unambiguous detection of methane both from Earth-bases observations (Krasnopolsky, Maillars & Owen (2004); Mumma, Novak, DiSanti, *et al.* (2004); Mumma, Novak, Hewagama, *et al.* (2005)) and from Mars Express Planetary Fourier Spectrometer data (Formisano, Atreya, Encrenaz, *et al.* (2004)) Both Formisano, Atreya, Encrenaz, *et al.* (2004) and Krasnopolsky, Maillars & Owen (2004) find similar average abundances on the order of 10 ppb. Mumma, Novak, DiSanti, *et al.* (2004) reports on much higher values of 250 ppb. The most intriguing part of the discovery is not just its detection, which has been tried since the early 1970's, but the fact that there seem to be large spatial and temporal variations of methane.

However, from photochemical considerations methane is expected to be homogeneouly mixed and to have a lifetime between 250 and 670 years (Nair, Allen, Anbar, *et al.* (1994); Krasnopolsky (1995); Wong & Atreya (2003)). If the observed variations are confirmed, then an additional and very efficient mechanism for methane destruction must be at work, in combination with localised and strong surface sources. One destruction mechanism could be by reaction with hydrogen-peroxide, which can be formed in large quantities in martian dust devils and dust storms by electrochemical processes (Atreya, Wong, Renno, *et al.* (2004)). Dust is present in the atmosphere of Mars everywhere and always. The

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origin of strong (sub)surface source is still quite unclear, but the past or present forms of life count among the possibilities.

At the surface clear evidence like the softness of rock interiors and high concentrations of sulphur and halogens indicates to the possibility of for past salty water. This evidence is being found by the Mars Exploration Rovers at their landing sites (Haskin, Wang, Jolliff, *et al.* (2005)).

4. Io

(Contributed by F. Marchis, University of California, Berkeley, USA)

With the end of the Galileo mission on September 21, 2003, and until the arrival of a new mission in the Jovian system (after 2010), the study of Io and its volcanism will lie again in the hands of ground-based observers.

Despite the large aperture of the recent telescopes built, the effect of atmospheric turbulence is still preponderant. The angular resolution of the images is limited to the seeing, *i.e.* about 0".7 in optical light from a very good site such as on the top of Mauna Kea in Hawaii, quite close to the angular diameter of Io (about 1".2) at its opposition. To break this "seeing barrier" and access the diffraction-limited resolutions of current telescopes (0".040 in the NIR on a 10-m telescope), several techniques have been proposed, which take advantage of the development of several technologies.

Thanks of its brightness, Io can be observed using speckle imaging (Macintosh, Gavel, Gibbard, *et al.* (2003)). However, this technique can be applied only when a very bright hot spot is visible on the individual images, since a reference is necessary for the shift-adding process. Consequently, it cannot be used most of the time to observe the satellite when it is sunlit.

The concept of Adaptive Optics was proposed by Babcock (1953), but it was only at end of the 1980s that the first prototypes were developed independently by groups based in the US and France. The AO systems provide in real-time an image with an angular resolution close to the diffraction limit of the telescope. Because of technological limitations linked to the wave front analysis, most of the current AO systems procure a correction that is partial and slightly variable in time in the NIR (1-5 μm). These systems were made available to the astronomical community on 4m-class telescopes less than 10 years ago.

Marchis, Prangé, Christou (2000) and Marchis, Prangé, Fusco (2001) have used the ADONIS AO system on the 3.6 m ESO telescope to monitor Io volcanic activity over a period of four year at a wavelength of 3.8 μm. The spatial resolution obtained in these observations was 0".15 or some 500 km on Io. At these long wavelengths, only the brightest hot spots (about 4 per hemisphere) could be seen against the sunlit disk of Io and the measure of their individual flux was difficulted by the limited angular resolution. With the advent of the 8m-class telescopes, the limit of detection for the hot spots on Io increases drastically. Approximately 5 to 8 active sources are detected on one 3-μm sunlit image using the AO system available on the Keck-10m telescope (Le Mignant, Marchis, Kwok, *et al.* (2003)) which provides an angular resolution of 0".05"at 2.2 μm, i.e. 130 km on Io at opposition. Because the hot spots can be also seen at longer wavelengths (5 μm), their temperature (between 500 and 1000 K) and emission area can be estimated (Marchis, de Pater, Le Mignant, *et al.* (2002)). In addition to these faint active centers Marchis, Le Mignant, Chaffee, *et al.* (2005) reports the detection of several active centers at shorter wavelength range (<2.5 μm) which have consequently a higher temperature (T > 1300K) and are more energetic. Photometric data over a large wavelength range (up to 1 μm on several occasions) allow the spectral profile to be estimated, making it possible to characterize their type of activity using a basaltic cooling lava flow model (Davies (1996)). Surt-2001, the largest eruption ever witnessed in the solar system, was luckily detected by Marchis' group at its beginning in Feb. 2001 with the Keck AO system. The intensity profile indicates the presence of a vigorous, high-temperature volcanic eruption (T $>$ 1400K) consistent with a basaltic eruption, and being a lower limit, do not exclude an ultramafic eruption. The kind of eruption to produce this thermal signature has incandescent fire fountains of molten lava which are kilometers high, propelled at great speed out of the ground by expanding gases, accompanied by extensive lava flows on the surface. Its integrated thermal output was close to the total estimated output of Io (about 10^{14} W, Veeder, Matson, Johnson, *et al.* (1994)).

On rare occasions (some 2 events per years), when Io is in the shadow of Jupiter and another Galilean satellite is located nearby (less than 30 arcsec), high spatial resolution eclipse AO images of the satellite can be recorded. In December of 2001, a total of 19 faint hot spots with a temperature up to 800 K were seen on the Jupiter-facing hemisphere. Their contribution to the global heat flow was 8% (de Pater, Marchis, Macintosh, *et al.* (2004a)),

Several AO systems are or will be soon available on 8m-class telescopes (MMT, GranteCan, LBT,.). The AO techniques became more reliable and accessible to a wider community. The extended temporal baseline of ground-based observations is significantly more important than intensive but short-baseline coverage provided by spacecraft. Current AO systems provide data with the same or better quality as most of the global Galileo/NIMS observations, *i.e.* about 200-300km (Douté, Schmitt, Lopes-Gautier, *et al.* (2001)).

A new generation of integral field spectrographs will be soon commissioned on several 8m-class telescopes, such as SPIFFI for the VLT-8m telescope and OSIRIS for the Keck-10 m telescope. They will give the opportunity to record in a few minutes a spectral cube of Io's surface with a much better spectral resolution than Galileo/NIMS (R = 1000–10000) between 0.9 and 2.5 μm helping to characterize the composition of the surface and the active volcanic centers. Long term monitoring, which can be provided from the ground only, is the key to understand the relation between the volcanism and surface changes on Io.

5. Saturn System and Titan

(Contributed by Régis Courtin, Observatory of Paris-Meudon, France; Jean-Pierre Lebreton, ESA/ESTEC, the Netherlands)

On July 1^{st} 2004, the Cassini spacecraft was succesfully inserted into Saturn's orbit after a voyage that lasted almost 7 years, and on January 14^{th} 2005, the Huygens probe reached Titan's surface after a dramatic 2.5 hours long descent through the thick hazy atmosphere of Saturn's largest moon. During the first fifteen months of an orbital tour that is expected to last 4-to-6 years, the investigations carried onboard the Cassini spacecraft have already contributed a significant number of discoveries about Saturn's atmosphere, its rings, the surface and interior of some of its icy moons (see reports in Science 307, 1222–1276), and about Titan (see reports in Science 308, 968–995).

On the other hand, the suite of instruments involved in the Huygens mission have returned a bonanza of breathtaking images, high-quality spectral data, as well as physical and chemical measurements that will take years to analyze fully. Huygens revealed an extraordinary world, resembling Earth in many respects, especially in meteorology,

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geomorphology, and fluvial activity. The images show strong evidence for erosion due to liquid flows, possibly methane, on Titan. The probe trajectory carried it across a boundary between a bright, icy, rugged terrain and a darker flat area. Huygens landed in the dark area. The measured pressure and temperature profiles below 150 km are close to those expected on the basis of Voyager observations. The measured surface temperature and pressure at the landing site were about 93.7 K and 1470 mbar respectively. At the landing site, the surface is relatively flat and solid. Reflectance spectra show that it is mostly composed of dirty water-ice. Water-ice pebbles up to a few centimeters in diameter were scattered near the landing site. Impact measurements found the surface to be unconsolidated, with the consistency of loose wet sand.

6. Uranus and Neptune

(Contributed by L. Sromovsky, University of Wisconsin, USA)

As Uranus approaches its 2007 equinox and Neptune reaches its 2005 southern summer solstice, new observing capabilities have revealed unexpected atmospheric activity on both planets and provided new results on dynamics, composition, and cloud structure.

Remarkably detailed adaptive optics images from the Keck 2 telescope have recently revealed many dozens of Uranus' cloud features (Fig. 1), far exceeding the number discovered by Voyager 2. With even more productive Keck 2 imaging of Neptune, this has resulted in improved wind profiles for both Neptune (Fry & Sromovsky (2004); Martin, de Pater, Gibbard, *et al.* (2004)) and Uranus (Hammel, de Pater, Gibbard, *et al.* (2005a); Sromovsky & Fry (2005a)). Unexpected oscillations were observed in Neptune's winds (Martin, de Pater, Gibbard, *et al.* (2004)) and new dynamical features were observed on Uranus, including a long-lived oscillating storm system (Sromovsky & Fry (2005a)), which is the first southern feature to become visible at 2 microns (Hammel, de Pater, Gibbard, *et al.* (2005b)). The brightest cloud feature ever observed on Uranus was recently seen in the northern hemisphere (Sromovsky & Fry (2005b)). Neptune's increasing visible brightness since 1980 (Lockwood & Thompson (2002)) and recently increasing cloud development (Sromovsky, Fry, Limay, *et al.* (2003)) may be partly seasonal effects, as may be the recent decline in Uranus' bright southern polar cap (Rages, Hammel & Friedson (2004)). The Keck 2 adaptive optics imaging has also permitted groundbased studies of ring structures of both planets (Gibbard, de Pater & Hammel (2004); de Pater, Gibbars, Chiang, *et al.* (2004b)). Recent radio imaging observations probing the 0.5 to 50 bar levels of Uranus' atmosphere (Hofstadter, Butler & Curwell (2005)) indicate the presence of large latitudinal gradients in composition (perhaps in the ammonia mixing ratio) or in temperature structure. In both hemispheres, latitudes poleward of 45 degrees were observed to be much brighter than lower latitudes, providing a hemispheric symmetry that contrasts with the asymmetry characterizing near-IR observations.

Spatially resolved near-IR spectral observations from Keck have determined pressure levels of 20 mb to 140 mb for 18 high-altitude bright discrete cloud features on Neptune (Gibbard, de Pater, Roe, *et al.* (2003)). The deeper cloud structures of both planets will soon be better understood using new models of the temperature dependence of methane absorption (Sromovsky, Irwin & Fry (2005c)) and new fits to laboratory observations at low temperatures (Irwin, Sromovsky, Strong, *et al.* (2005)). Spectral observations at longer infrared wavelengths have improved our knowledge of stratospheric compositions and photochemistry. Burgdorf, Orton, Davis, *et al.* (2003)) used used 1996-1997 Infrared Space Observatory observations from 28 to 144 microns to derive a He mole fraction that confirms the recently questioned results from Voyager-2. Spitzer Space Telescope

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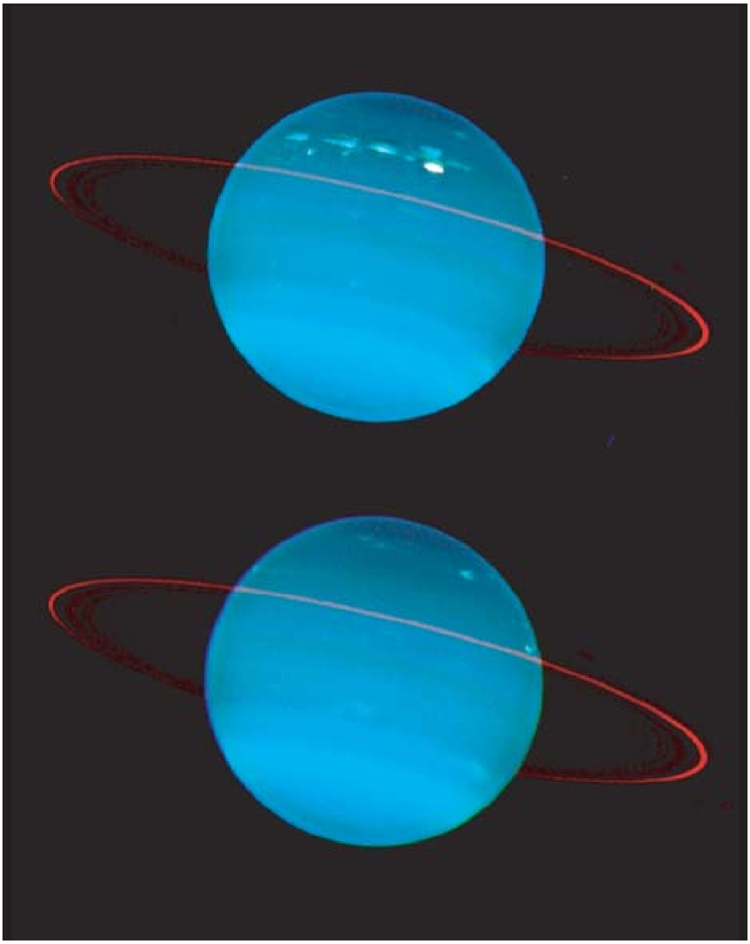

Figure 1. Keck 2 image of Neptune (explanation, see text)

observations between 5 and 38 microns have found evidence for several new hydrocarbons on Uranus and Neptune and evidence for temporal variation (Orton, Burgdorf, Meadows, *et al.* (2005)). Detection of CO on Uranus using the 8-meter VLT weakly suggests that it may be external in origin (Encrenaz, Lellouch, Drossart, *et al.* (2004)). Mid IR spectroscopy of Neptune from the NASA IRTF has shown significant variations in Neptune's 12-micron ethane emission (Hammel, Sitko, Lynch, *et al.* (2005c)).

Continued groundbased adaptive optics imaging and spectroscopy at near IR wavelengths and as well as microwave imaging and longer wavelength spectral observations will help answer many remaining questions about the role of seasonal solar forcing of the atmospheres, the location and composition of the main cloud layers, and the reason for an apparently strong depletion of ammonia in both tropospheres.

7. Small Satellites of the Giant Planets

(Contributed by S. Sheppard, Carnegie Institution of Washington, USA)

The years 2002 to 2005 saw a large increase in the number of small satellites known around the giant planets. Jupiter's retinue grew with 24 outer satellites with diameters

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(D) of 2 to 4 km discovered by Sheppard & Jewitt (2003) and Gladman, Sheppard & Marsden (2003) using wide-field CCDs on medium to large telescopes, 13 outer satellites with D of 4 to 7 km were discovered around Saturn in 2004 by Jewitt, Sheppard, Kleyna, *et al.* (2005a) as well as at least 4 small inner satellites have been discovered by the Cassini imaging team with D of 3 to 7 km, Uranus had 3 new outer satellites discovered with D of 20 to 22 km by Kavelaars, Holman, Grav, *et al.* (2004) and Sheppard, Jewitt, Kleyna (2005) and two new inner satellites with D of 10 km were discovered by Showalter and Lissauer with the HST in 2003, and Neptune had 5 new outer satellites discovered with diameters between 38 and 61 km by Holman, Kavelaars, Grav, *et al.* (2004) and Sheppard, Jewitt, Kleyna (2005).

These discoveries nearly doubled the known giant planet outer satellites to 96 which is more than the 51 known giant planet regular satellites. The outer irregular satellites have large eccentricities, inclinations and semi-major axes and thus are believed to have been captured from Heliocentric orbits. It appears that all the giant planets have similar outer irregular satellite systems with each having a population of about 100 larger than 1 km, a shallow size distribution and similar orbital configurations irrespective of the host planet's mass or formation scenario (Sheppard, Jewitt, Kleyna (2005)). These observations make the favored capture mechanism that of collisional or collisionless interactions occurring within the Hill spheres of each planet just after the planet formation epoch when such interactions would have been most probable (Jewitt & Sheppard (2005b)). This capture mechanism is fairly independent of the mass or formation scenario of the planet. Because the less massive ice giants are more distant from the Sun their Hill spheres are actually larger than the gas giants. These increased Hill spheres may compensate for the lower density of small bodies in the outer solar nebula and thus allow all the giant planets to capture similar irregular satellite systems. Agnor & Hamilton (2004) have recently shown that this type of capture would work well for Neptune's Triton.

Three body interaction capture also agrees with the results of Beauge, Roig, Nesvorny (2002) in which they find the irregular satellites would have to have formed after any significant planetary migration or scattering as suggested by Morbidelli, Levison, Tsiganis, *et al.* (2005). It also agrees with Brunini, Parisi, Tancredi (2002) who find that Uranus' irregular satellites would have to be captured after any impact which would have tilted the planets rotation axis. Triton would have disrupted the outer satellites of Neptune and capture of these irregulars probably occurred after Triton was captured (Cuk & Gladman (2005)).

High inclination orbits have been found through numerical simulations to be unstable do to solar perturbations which agrees with observations (Carruba, Burns, Nicholson, *et al.* (2002); Nesvorny, Alvarellos, Dones, *et al.* (2003)). A number of the new irregular satellites have been found to be in orbital resonances with their planet. These resonances protect the satellites from strong solar perturbations (Nesvorny, Alvarellos, Dones, *et al.* (2003); Cuk & Burns (2004)). The evolution of satellites into these resonances implies some sort of slow dissipation mechanism which allowed the satellites to acquire the resonances. This could be obtained from weak gas drag, a small increase in the planet's mass or a slow migration of the planet.

Recent colors measurements of the irregular satellites show them to be neutral to moderately red (Grav, Holman, Gladman, *et al.* (2003); Grav, Holman, Fraser (2004a)). Most do not show the very red material found in the distant Kuiper Belt. Near-infrared colors recently obtained of the brighter satellites agree with this scenario and that the Jupiter irregular's colors are consistent with D and C-type asteroids (Grav & Holman (2004b)). Near-Infrared and optical spectra of the brightest Jupiter outer satellites are mostly linear and featureless (Chamberlain & Brown (2004); Geballe, Dalle, Cruikshank, *et al.* (2002)).

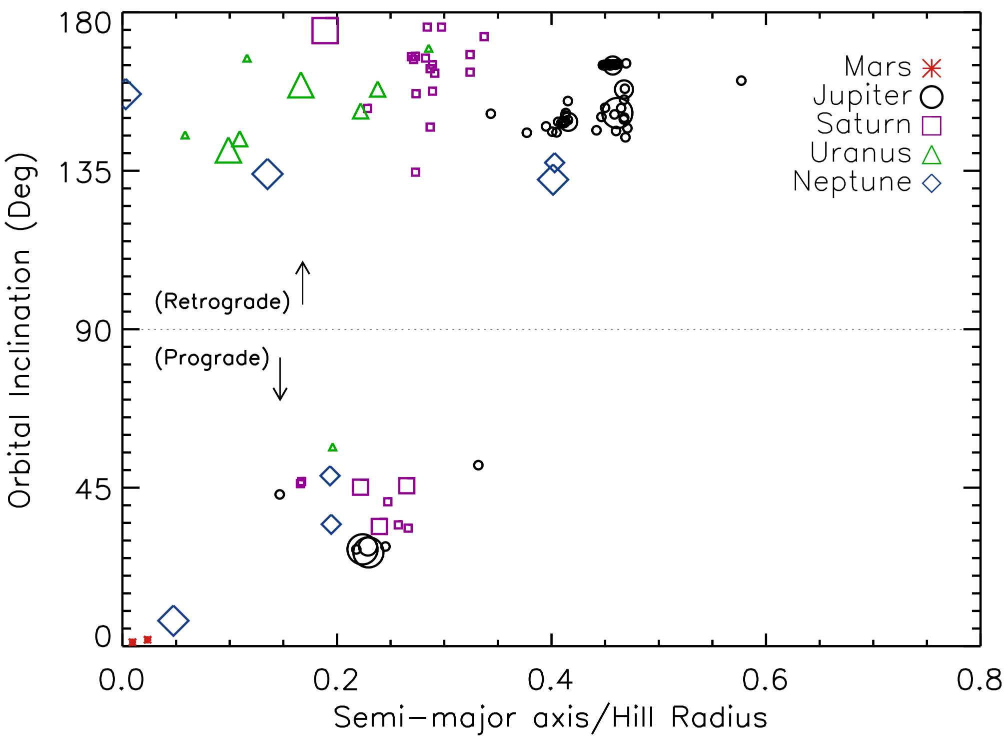

Figure 2. All 96 Known irregular satellites of the giant planets. The horizontal axis is the ratio of the satellites semi-major axis to the respective planet's Hill radius. The vertical axis is the inclination of the satellite to the orbital plane of the planet. The size of each satellite is represented by the symbol size. Mars' two satellites are plotted for comparison. All 51 known regular satellites would fall near the origin of this plot. Modified from Sheppard, Jewitt, Kleyna (2005)

Saturn's Phoebe appears remarkably different. Cassini passed 2071 km above Saturn's irregular satellite Phoebe on June 11, 2004. The images showed Phoebe to be intensively cratered with many high albedo patches near crater walls (Porco, Baker, Barbara, *et al.* (2005)). Phoebe's density was found to be 1630 ± 33 kg m^{-3} (Porco, Baker, Barbara, *et al.* (2005)). The spectra showed clear evidence for the existance of large amounts of of water ice as well as ferrous-iron-bearing minerals, bound water, trapped CO_2, phyllosilicates, organics, nitriles and cyanide compounds on the surface (Clark, Brown, Jaumann, *et al.* 2005). Phoebe's volatile rich surface and many compounds infer the object was formed beyond the rocky main belt of asteroids and maybe very similar to the composition of comets. Finally, Buratti, Hicks, Davies (2005) show that the color of the dark side of Iapetus is consistent with dust from the small outer satellites of Saturn.

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