COMMISSION 16: PHYSICAL STUDY OF PLANETS & SATELLITES
ETUDE PHYSIQUE DES PLANETS & SATELLITES

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1. INTRODUCTION

The study of the physical properties of planets and satellites has flourished since the beginning of direct space exploration in the 1960s. Although the pace of planetary exploration has declined since its peak (roughly from 1970 to 1986), this field remains strong and productive. The level of research activity was approximately the same as in the previous report period, with the publication of more than a thousand research papers. This activity is broadly international, and growth in planetary research has been especially notable in Europe. The two most important annual meetings of planetary scientists are the Division for Planetary Sciences (DPS) of the American Astronomical Society, held each autumn, and the Lunar and Planetary Science Conference, held each spring at Houston. Both meetings attract between 300 and 600 registrants, with a comparable number of papers presented. The primary journals for publication of planetary science are *Icarus* and the *Journal of Geophysical Research*, although many other astronomical and geoscience journals play an important role, as well as the two general-science journals *Science* and *Nature*.

Highlights of planetary exploration and research during this reporting period (1990-1992) included: (1) radar mapping of the surface of Venus at 100 m resolution by Magellan, generating a data set from which to determine the geology and evolutionary history of the planet; (2) continuing strong interest in Mars, in part focused toward eventual human presence on that planet; and (3) analysis of results from the 1989 Voyager flyby of Neptune and Triton. Other events of note include the end of the 13-year Pioneer Venus studies as the spacecraft entered the atmosphere of the planet, two productive flybys of the Earth-Moon system by the Galileo spacecraft, and a growing interest in the Pluto-Charon system. This field is increasingly interdisciplinary, involving astronomers, geoscientists, physicists, and biologists, and motivated by interest in understanding the origin and evolution of the planets.

Although the present review attempts to mention the most important new results in the physical study of planets and satellites, it can cite individually fewer than 25% of the papers actually published in this field during 1990-92. The selection of papers to cite is partly subjective. In general, there has been an effort to emphasize astronomical work over that which is primarily of a geological or geochemical nature, or that which can be classified as space physics. Major research areas dealing with the analysis of lunar samples and martian samples (the SNC meteorites) are not included due to limitation in space. For complementary reviews of current research the reader is referred to reports from Commissions 15, 22, and 51.

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2. MERCURY

Mercury is a difficult planet to observe, and it has been visited by only one spacecraft, Mariner 10, which made 3 flybys in 1974/75. Limited progress has been made since Mariner 10 in understanding the geology and crustal evolution of the planet, but continuing interest in the dynamics of the inner solar system has connected the anomalous high density of Mercury with the era of catastrophic collisions. A giant impact could have removed much of the mantle of Mercury not long after the planet differentiated, leaving the present silicate-depleted object.

Earth-based spectroscopy of Mercury has revealed additional details of its tenuous atmosphere of sodium and potassium, which appears to be the result of diffusion upward through the crust (Sprague *et al., Icarus* **84**:93; Killian *et al., Icarus* **85**:145). Enhancement of K has also been reported above the Caloris basin (Sprague *et al., Science* **249**:1140). Sprague (*J. Geophys. Res.* **97**:18257) proposed a model for Na and K variability based on ion implantation into the regolith during the long mercurian night with subsequent diffusion to the atmosphere as temperatures rise. Ludlow *et al.* (*Astrophys. J.* **384**:640) have used the VLA to obtain high-resolution maps of thermal emission from the planet.

Perhaps the most surprising new result on Mercury in this triennium was the discovery of greatly enhanced radar reflectivity from high latitudes, which is interpreted as near-surface polar ice (Slade *et al., Science* **258**:635; Harmon *et al., Science* **258**:640; Paige *et al., Science* **258**:643). The observations, which were made with both the Arecibo and Goldstone radars, confirm the presence of such ice caps at both poles (Butler *et al., J. Geophys. Res.* **98**:15005), but the ability of the planet to retain ice over the history of the solar system is unexplained.

3. VENUS

During this reporting period, Venus received more attention than any other member of the planetary system. The Pioneer Venus orbiter continued its long series of observations of the upper atmosphere and space environment of the planet until its orbit decayed in October 1992. During the final months of the mission the Pioneer spacecraft sampled regions of the atmosphere at lower elevations than had been studied directly previously. Excellent atmospheric results were also obtained during the February 1990 flyby of Venus by the Galileo spacecraft (Johnson *et al., Science* **253**:1516). In the early part of this triennium, analysis continued of the radar maps of the planet at resolutions of 1-2 km obtained by the Venera 15 and 16 orbiters and the Arecibo and Goldstone ground-based radars. However, these radar results were quickly superseded when the Magellan spacecraft began its mapping mission in September 1990. The Magellan radar images have revolutionized our understanding of the geology and geological history of Venus, as described further below.

Results on atmospheric dynamics as derived from differential VLBI measurements of the VEGA balloons were reported by Sagdeyev *et al.* (*Astron. Astrophys.* **254**: 387), and Schinder *et al.* (*J. Atmos. Sci.* **47**:2037) discussed the formation of waves, advection, and cloud patterns. However, issues of chemistry, origin, and evolution continued to be the focus of most observational and theoretical work on the atmosphere of Venus. Infrared and millimeter observations yielded detection of HDO and determination of the abundance of deuterium. De Bergh *et al.* (*Science* **251**:547) obtained $D/H = 120 \pm 40$ at altitudes near 40 km. Encrenaz *et al.* (*Astron. Astrophys.* **246**:L63) used IRAM data to derive a mixing ratio of water below 95 km of 3.5 ppm, while Crisp *et al.* (*Science* **253**:1263) used IR observations to derive a mixing ratio

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of 40 ± 20 ppm. In a summary of all the deuterium and water abundance data, Donahue & Hodges (*J. Geophys. Res.* **97**:6083) argued that the mixing ratio for atmospheric water increases by a factor of 4 between the surface and 10 km altitude to a value of 150 ppm and drops to 10 ppm above 50 km. These results require large-scale temporal and spatial variations; these authors also conclude that the early Venus must have been endowed with at least 2 orders of magnitude more water above the surface than is presently there. Fegley (*Astron. Vest.* **26**:3) reviewed the chemistry of the surface and lower atmosphere, using atmospheric data to infer information on surface chemistry. Kaula (*Science* **247**:1191) suggested that the current dry atmosphere is a consequence of low levels of crustal turnover, which in turn are related to the absence of a large satellite of Venus. Many authors considered the structure of the ionosphere and thermosphere, and the interaction of Venus with the solar wind, based on both Pioneer Venus and Galileo data (*e.g.*, Bougher *et al.*, *J. Geophys. Res.* **95**:6271; Kim *et al.*, *J. Geophys. Res.* **95**:6569, Kivelson *et al.*, *Science* **253**:1518; Hord *et al.*, *Science* **253**:1548). A detailed exposition of this work through about 1990 appears in the book *Venus Aeronomy,* edited by Russell and published in 1991 by Kluwer, while a more recent review is by Luhmann *et al.* (*J. Geophys. Res.* **96**:11019).

The Magellan spacecraft was launched on 4 May 1989 and began its radar mapping mission on 15 September 1990. The spacecraft utilized a single radar sensor to collect synthetic aperture images, radar altimetry, and radiometric data at 2.4 Ghz. Nominal imaging resolution was about 100 m. The first 8-month cycle imaged 84% of the planet with left-looking radar. The second cycle used right-looking radar and increased the coverage to 97%. Cycle 3 (ending in September 1992) was again left-looking and yielded considerable stereo coverage. In 1993 aerobraking was used to lower and circularize the orbit for enhanced mapping of the planet's gravity field. A series of papers summarizing the state of knowledge just before Magellan appeared in *Earth Moon Planets* **50/51**:3-558, and an account of much of the earlier Russian work on Venus is found in the book *Venus Geology, Geochemistry, and Geophysics: Research Results from the USSR,* edited by Barsukov *et al.* and published by the University of Arizona Press. An early summary of Magellan results was published by Saunders *et al.* (*Science* **252**:249); however, the bulk of the initial scientific results from Magellan (primarily interpretation of data from cycle 1) were published in 50 papers printed in two special editions of *J. Geophys. Res.* dated 25 August 1992 (**97**:13067-13689) and 15 October 1992 (**97**:15921-16380).

Magellan provided a fundamental data set for assessment of global volcanism, tectonism, impact processes, and surface processes on Venus. The mean radius is 6051.84 km, and more than 80% of the surface lies within 1 km of this elevation. The rotation period is 243.0185 days, and the north pole position is RA 272.76, dec 67.16 (Saunders *et al.*, *J. Geophys. Res.* **97**:13067). Most of the surface is either volcanic plains (85%) or complex ridged terrain or tessera, including highland plateaus and mountains. Volcanism is widespread, with thousands of individual volcanic constructs including shield volcanoes and cinder cones, down to the 100-m resolution of the images. The most extensive units consist of flood lavas. A number of distinctive volcanic features have been identified, including "pancake" domes (circular, flat-toped constructs of highly viscous lava) and lava channels or rivers of remarkable size. Hildr, the longest lava channel, is more than 6000 km long, yet of nearly uniform width. The planet has been subject to extensive tectonic deformation, and the resulting ubiquitous folds and cracks are readily seen in radar images at all scales. There are a few large offset faults, but most of the evidence suggests local shear and relatively small-scale tectonic features. While there is no indication of global plate tectonics such as that experienced by the Earth, there are regions of both extension (rifting) and convergence (producing folded mountains). The steep mountains of

Ishtar Terra suggest the presence of currently active tectonic deformation, presumably supported by a large mantle plume. Mantle upwelling is further suggested by correlation of large shield volcanoes with geoid anomalies. Among the most distinctive features of the geology of Venus are coronae, which are large circular tectonic features characterized by both concentric and radial cracks, often associated with volcanic activity. The coronae appear to be supported by mantle plumes, and many are probably an intermediate stage leading toward volcanism and surface rifting.

Nearly 1000 impact craters have been discovered on the surface of Venus. They range from large multiring basins (up to nearly 300 km diameter) to simple craters some tens of km in diameter, often with flooded floors and extensive surrounding flows due to fluidized ejecta or induced volcanic activity. Below a diameter of 35 km, there are fewer craters than would be expected from lunar comparisons, as a consequence of shielding by the atmosphere. At smaller sizes, craters are replaced by radar-dark (smooth) regions apparently resulting from atmospheric disintegration of incoming projectiles; the atmospheric breakup of meteoroids has been modeled by Zahnle (*J. Geophys. Res.* **97**:10243). Also distinctive are large dark paraboloidal surface features associated with some younger craters. Surprisingly, abundant wind streaks have also been identified on the surface. The estimated surface age from crater density is between 200 and 700 million yr with no clear indication of substantial local variations in age. Since only a small percentage of the craters have been modified by flooding or other geological activity since they were formed, one interpretation of the crater statistics is that there was a global resurfacing of Venus several hundred million years ago, in which most of the crust was renewed at about the same time. Intensive analysis of the Magellan data is continuing; it is notable that this mission has returned more data than all previous planetary missions combined.

4. MOON

Lunar science is a healthy and active part of solar system studies, with most research still focused on the analysis and interpretation of samples returned by the Apollo and Luna missions of the early 1970s. Dozens of papers in lunar science are presented at the Lunar and Planetary Science Conference held each spring in Houston. We will not attempt to review this body of information on lunar geology and geochemistry in the current brief overview; the interested reader is directed to the various publications and bibliographies available from the Lunar Science Institute in Houston.

The thin, transient atmosphere of the Moon has been studied by several researchers, stimulated in part by discovery of a similar atmosphere on the planet Mercury (Morgan & Shemansky, *J. Geophys. Res.* **96**:1351). A group of related papers deal with the presence of sodium and its possible time variability (Potter & Morgan, *Geophys. Res. Lett.* **18**:2089; Ip, *Geophys. Res. Lett.* **18**:2093; Mendillo *et al., Geophys. Res. Let.* **18**:2097; Hunten *et al., Geophys. Res. Lett.* **18**:2101).

Preliminary results from the Galileo spacecraft encounter with the Earth-Moon system of December 1990 were presented by Belton *et al.* (*Science* **255**:570). The geometry of the flyby was such that the western limb of the Moon was illuminated, in contrast to the Apollo missions, providing unique data on the Orientale basin and parts of the lunar farside highlands that had not been well observed previously. The primary data set discussed by Belton *et al.* consists of multispectral images obtained with the Galileo CCD camera, which provide sensitive discrimination of various mineralogic units. Observations of the South Pole-Aitken basin (which is more than 2000 km in diameter) suggest that this impact, one of the largest preserved in the lunar record, penetrated into the mantle, unlike the Orientale basin, which appears to sample only crustal material. A second Earth-Moon flyby took place in December 1992.

5. MARS

The study of Mars is central to the discipline of planetary science. This is probably the best observed of all the planets, and the Viking missions of 1976 provided a level of *in situ* data that is exceeded only for the Moon, where humans have landed. Mars is, in many respects, the planet most like the Earth, and during this triennium it took on added significance from efforts within the United States to promote efforts leading toward human exploration early in the next century. Although these efforts (the "Space Exploration Initiative") were largely abandoned in 1993, they served to focus both scientific and general interest on this planet.

A major book entitled *Mars* (edited by Kieffer, Jakosky, Snyder, and Matthews) was published in 1992 by the University of Arizona Press, consisting of 38 chapters by 114 authors. This volume serves as a concise scientific summary of our knowledge of Mars at the time of its publication. It is organized to present 4 introductory chapters, 6 chapters on solid body geophysics, 6 chapters on bedrock geology and geologic units, 7 chapters on surface properties and processes, 10 chapters on the atmosphere, 2 chapters on biology, and 3 chapters on the martian satellites Phobos and Deimos. It is impossible in this brief overview of progress in planetary studies to summarize the contents of this book, or of the dozens of subsequent papers dealing in even greater detail with many of these same topics. In this review we will briefly discuss a few of the additional publications on Mars that have appeared since the University of Arizona volume. A growing body of information is derived from analysis of the SNC meteorites, which are samples of martian material ejected and transported to Earth, but we will not review that material here, since meteorites are discussed under Commission 15.

Publication has continued in this triennium of data and interpretation from the Phobos-2 mission. Surkov *et al.* (*Pis'ma Astron. Zh.* **16**:355) reported on remote determination of the fundamental composition of the martian crust, concluding that much of the surface consists of subalkaline basalt, while interpretation of the VSK and KRFM investigations was presented by Murchie *et al.* (*J. Geophys. Res.* **96**:5925). A series of papers on the Phobos-2 plasma results appeared in *Geophys. Res. Lett.* **17**:869-900; e.g., a discussion by Luhmann *et al.* (*Geophys. Res. Lett.* **17**:869) of the similarities between the solar wind interactions at Mars and Venus. The general issue of the martian ionosphere and magnetosphere was reviewed by Luhmann (*Rev. Geophys.* **29**:121).

One of the surprises of the Viking mission was the discovery that only the southern polar cap of Mars is able to retain frozen carbon dioxide throughout the year. This difference and the general issue of the stability of the polar caps were addressed by Jakosky & Haberle (*J. Geophys. Res.* **95**:1359), who concluded that the fate of the caps depends critically on the rate of heat conduction into the underlying soil. Carr (*Icarus* **87**:210) discussed the interpretation of the recent measurements of the D/H ratio on Mars, examining the effects of surface processes such as flood volcanism, impacts, and the formation of polar deposits. He concluded that the observed value of D/H in Mars (5 times greater than on Earth) depends on the rate of *exchange of water between the atmosphere and polar deposits. Jakosky (Icarus 94:14) also* considered volatile evolution of Mars, analyzing how the observed fractionation of oxygen, carbon, and hydrogen is produced by exchanges among the atmosphere, regolith, and caps.

An important focus of current Mars studies is the evolution of the surface and atmosphere through time. Haberle has edited a special report on this topic published in *J. Geophys. Res.* **98**:3091-3482 and **98**:10897-11121. Here more than 100 authors, in 38 papers, review such topics as surface mineralogy and geology, atmospheric origin and evolution, current climate and atmospheric dynamics, fluvial processes, ground ice distribution, and the SNC meteorites. Of particular value are three papers that discuss the NASA Ames general circulation model (GCM) for the martian atmosphere, a sophisticated computer code that is able to simulate the dynamics of the martian atmosphere using appropriate boundary conditions such as, for example, the correct distribution of surface topography (Haberle *et al., J. Geophys. Res.* **98**:3093; Barnes *et al., J. Geophys. Res.* **98**:3125; Pollack *et al., J. Geophys. Res.* **98**:3149).

One reason for interest in the evolution of the atmosphere and climate of Mars is to assess the probability of the origin of life and to identify possible sites for martian fossil organisms. Many of these are exobiological issues, discussed in the report of Commission 51 on Bioastronomy. Rothshild *et al.* (*Icarus* **88**:246) discussed the possibility of preserving martian microbes in evaporites, which might be found in paleolakes on Mars. The more general issue of ancient aqueous sedimentation on Mars was explored from a geological perspective by Goldspiel & Squyres (*Icarus* **89**:392), who identified 36 sites, concentrated in ancient cratered terrain between the equator and latitude 30 S, where ponding of water probably occurred. The question of the possible duration of such liquid water habitats was addressed by McKay and Davis (*Icarus* **90**:214). The more remote possibility of currently extant life forms on Mars was discussed by Boston *et al.* (*Icarus* **95**:300) in an analysis of chemosynthetic ecosystems in subsurface habitats.

6. JUPITER

Extensive Earth-based observations of Jupiter continue to be made, in part to provide continuity between the Pioneer and Voyager flybys of the late 1970s and the arrival of the Galileo orbiter and probe in 1995. An International Jupiter Watch (IJW) is coordinating many of these observations. The Galileo mission was successfully launched and completed its tour of the inner planets preparatory to the flight to Jupiter. Failure of the spacecraft high-gain antenna to deploy will substantially restrict the quantity of data that can be transmitted from Jupiter; this will not be a problem for the probe mission, but it will certainly have an impact on the orbital operations. Russell has edited a comprehensive book called *The Galileo Mission* (Kluwer); the same papers are also available in *Space Sci. Rev.* **60**.

Jupiter remains the prototype giant planet, and the one for which we have the best data on atmospheric dynamics. Conrath *et al.* (*Icarus* **83**:255) discussed the temperatures and circulation in the stratospheres of the jovian planets, while Ingersoll (*Science* **248**:308) reviewed models comparing their atmospheric dynamics. All four jovian planets have longitudinal banding and high-speed jet streams. Jupiter is the most active, while Saturn and Neptune have the highest wind velocities. Two general classes of fluid dynamical models have been developed to reproduce many of the observed features of winds, temperatures, and cloud patterns: those that consider only the atmosphere itself, and those that include circulation in the deep liquid mantles. A comparative analysis of the interior structures of the jovian planets has been published by Zharkov (*Astron. Vest.* **25**:627)

There is considerable interest in the possibility of detecting global oscillations of Jupiter in order to apply the techniques of helioseismology to probing conditions in the planet's interior. Tentative detection of oscillations with periods of tens of minutes was reported by Schmider *et al.* (*Astron. Astrophys.* **248**:281) and discussed by Mosser *et al.* (*Astron. Astrophys.* **251**:356 and *Icarus* **96**:15).

Infrared observations of auroral emissions in the upper atmosphere were reported by Kim *et al.* (*Nature* **353**:536) and Baron *et al.* (*Nature* **353**:539), while Livengood *et al.* (*Icarus* **97**:26) provided a summary of jovian ultraviolet auroral activity as observed by IUE from 1981 to 1991. Carlson *et al.* (*Astrophys. J.* **388**:648) found from a reanalysis of Voyager IR spectra that it is possible in jovian hot spots to probe atmospheric composition down to a pressure level of 5 bars; they find a relatively high abundance of water vapor, probably about twice the solar mixing ratio. De Pater has published two extensive reviews of microwave spectra and imaging of the giant planets (*Phys. Rep.* **200**, 1; *Ann. Rev. Astron. Astrophys.*), discussing both their atmospheres and magnetospheres.

7. SATURN

Recent interest in Saturn has concentrated on its atmosphere, particularly on the appearance of a major equatorial disturbance called the "great white spot" (Westphal *et al.*, *Astrophys. J.* **369**:L51; Sanchez-Lavega *et al.*, *Nature* **353**:397; Beebe *et al.*, *Icarus* **95**:163; Westphal *et al.*, *Icarus* **100**:485). Other results on Saturn's atmosphere and magnetosphere are included in the papers comparing the jovian planets cited above in Section 6.

8. URANUS

A comprehensive book on this planet and its satellite and ring system was published in 1991: *Uranus*, edited by Bergstralh, Miner, and Matthews, University of Arizona Press. A total of 21 papers by 86 authors summarized the results from the 1986 Voyager-2 flyby and subsequent interpretation. A more popular account by Miner is found in *Uranus: The Planet, Rings, and Satellites* (Ellis Norwood Library). After the 1989 Voyager flyby of Neptune, models for the interiors and structure of Uranus and Neptune were compared by Hubbard *et al.* (*Science* **253**:648) and Podolak *et al.* (*Geophys. Res. Lett.* **17**:1737).

9. NEPTUNE

Voyager 2 completed its grand tour of the solar system with a flyby of Neptune and Triton in August 1989; thus most analyses of these new data fall within the current triennium. Many of the initial results were published in 32 papers in a special issue of *Geophys. Res. Lett.* **17**:1661-1776 (September 1990), and a later more extensive series of papers appeared in a special issue of *J. Geophys. Res.* **96**:18907-19268 (30 October 1991), and in *Icarus* **99**:241-435 (October 1992). A popular-level account of the Neptune encounter is to be found in *Far Encounter: The Neptune System* by Burgess (Columbia University Press), while a multi-author technical volume called *Neptune* is in preparation in the Space Science Series of the University of Arizona Press.

Unlike Uranus, Neptune has a substantial internal heat source. Voyager IR observations (Pearl *et al.*, *J. Geophys. Res.* **96**:1829) yield a bolometric bond albedo of 0.29, a calculated equilibrium temperature of 47 K, but an observed effective temperature of 59 K, implying an energy balance given by $E = 2.6 \pm 0.3$. Voyager IR data also yielded abundances of acetylene and ethane (Bezard *et al.*, *J. Geophys. Res.* **96**:18961), while Rosenqvist *et al.* (*Astrophys. J.* **392**:L99) used millimeter spectra obtained with the IRAM telescope to measure the mixing ratios of CO and HCN on Neptune. De Bergh *et al.* (*Astrophys. J.* **355**:661) discovered monodeuterated methane in the spectrum of Neptune and derived a D/H mixing ratio of 0.00012, indicating that deuterium is strongly enhanced (as it is also for Uranus). Voyager imaging data allow determination of atmospheric zonal winds from observed displacement of cloud features (Limaye *et al.*, *J. Geophys. Res.* **96**:18941).

The orientation and strength of the magnetic field are similar to those of Uranus, displaying a dipole tilt of 47 degrees as well as a major offset from the center of the planet (Voigt & Ness, *Geophys. Res. Lett.*, **17**:1705; Connerney *et al.*, *J. Geophys. Res.* **96**:19023). A great many authors report on aspects of the magnetosphere and plasma environment of Neptune in these two special journal issues. A comprehensive comparative study of the magnetospheres of all four jovian planets was published in 1991 by Baganel (*Ann. Rev. Earth Planet. Sci.* **20**:289)

10. PLUTO-CHARON

The outermost planet and its satellite continue to yield their secrets to studies with large telescopes, assisted by the fact that the planet passed through perihelion in 1989. Although Pluto is now the only planet not to have been visited by a spacecraft, there is currently considerable interest in the United States in flying a fast flyby that would reach the planet before increasing distance from the Sun causes its atmosphere to freeze out on the surface. A biography by Levy titled *Clyde Tombaugh: Discoverer of Planet Pluto* was published in 1991 by the University of Arizona Press, and an international meeting on Pluto was held in 1993.

A number of papers have dealt with results from the mutual occultation events of the late 1980s (e.g., Elliot & Young, *Icarus* **89**:244; Blanco *et al.*, *Astron. J.* **101**:2262; Buie, *Icarus* **97**:211), which have yielded both fundamental constants of the system and albedo maps of Pluto. Observations with the Hubble Space Telescope (Albrecht *et al.*, *Astrophys. J.* **374**:L65) improved the value for the separation of Pluto and Charon and hence the mass of the system, and they also hint at a difference in density between the two objects. The diameter of Pluto is now known to be 2300 km and its density is 2.1, suggesting a composition roughly 75% silicate and 25% ice. The diameter of Charon is 1200 km. The most spectrally active component of the surface of Pluto is methane, but this is only a trace constituent, with nitrogen emerging as the likely candidate for the most abundant molecule in the crust.

Although exceedingly tenuous, the atmosphere of Pluto continues to represent an area of research interest. Non-thermal atmospheric models were published by Hubbard *et al.* (*Icarus* **84**:1), while Clark *et al.* (*Icarus* **95**:173) carried out an analysis of the extended atmosphere predicting that dissociation of methane would lead to an extensive hydrogen corona; they searched for Lyman-alpha emission with the IUE but were able only to set an upper limit. A comprehensive review of the Pluto-Charon system was published by Stern in 1992 (*Ann. Rev. Astron. Astrophys.* **30**:185)

11. GALILEAN SATELLITES

Improved monitoring of the volcanic activity on Io has become possible with increases in spatial resolution achieved by infrared telescopes, which now permit the thermal emission from different "hot spots" to be measured separately. Spencer *et al.* (*Nature* **348**:618; *Science* **257**:1507) carried out a series of disk-resolved observations at better than 0.2 arcsec resolution with the IRTF that distinguished several eruptive centers during eclipses and allowed the brighter eruptions to be followed in full sunlight. McLeod *et al.* (*Astron. J.* **102**:1485) used the MMT to achieve a similar resolution; they were able to detect activity from Pele for the first time since the Voyager flybys. Such observations should provide a good baseline on Io volcanism as we approach the 1995 arrival of Galileo.

New infrared observations and laboratory spectroscopy have revealed minor constituents of the surface of Io, including both H_2O and H_2S, which are the first hydrogen-bearing molecules identified (Salama *et al.*, *Icarus* **83**:66). Ices containing 3% H_2S and 0.1% H_2O provide a good fit to observed spectra. The IUE (Ballwester *et al.*, *Icarus* **88**:1) and IRAM (Lellouch *et al.*, *Nature* **346**:639) have been used to measure the SO_2 atmosphere of Io; Lellouch *et al.* conclude that the neutral SO_2 is in equilibrium with surface frost, buffered by the colder (higher-albedo) surface traps. Structure of the extended corona of gas around Io was discussed by Schneider *et al.* (*Astrophys. J.* **368**:298), and ultraviolet observations of the Io torus from the 1990 ASTRO-1 mission were reported by Moos *et al.* (*Astrophys. J.* **382**:L105).

The extraordinary radar echoes (high reflectivities and a large amount of polarization in the opposite sense from that expected in a single reflection) from Europa, Ganymede, and Callisto are a continuing source of information on the crusts of icy satellites. Ostro & Shoemaker (*Icarus* **85**:335) discussed electromagnetic scattering for a variety of geological models of the regolith of icy objects. An alternative model including coherent backscatter was published by Hapke (*Icarus* **88**:407). New observational data from both Arecibo and Goldstone presented by Ostro *et al.* (*J. Geophys. Res.* **97**:18277) suggest that radar reflectivity may provide a crude indicator of relative silicate abundance, and also indicate first detection of several albedo features, including Galileo Regio (Ganymede) and Valhalla (Callisto).

After more than a decade of work, the Voyager images of the Galilean satellites continue to be used by planetary geologists. For example, Thomas and Squyres (*J. Geophys. Res.* **95**:19161) discussed crater palimpsests on Ganymede and offered a model that includes volcanism triggered by impact, and Shenk (*J. Geophys. Res.* **96**:15635) analyzed the cratered units of Callisto and Ganymede to find systematic differences in crater morphology.

12. TITAN

The atmosphere of Titan remains a subject of substantial interest, stimulated by plans for the Cassini mission with its Huygens entry probe. Sicardy *et al.* (*Nature* **343**:350) and Hubbard *et al.* (*Nature* **343**:353) discussed results on upper atmospheric structure revealed by the occultation of the star 26 Sag on 3 July 1989, which effectively probed an altitude range from 250 to 500 km and yielded a mesospheric temperature of 180 K. Toon *et al.* (*Icarus* **95**:24) and Cabane *et al.* (*Icarus* **96**:176) discussed physical and chemical models for Titan aerosols, and dynamical models for the ionosphere were presented by Ip (*Astrophys. J.* **362**:354).

Radar was used to distinguish among surface models of Titan on the basis of the

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observed reflectivity. Muhleman *et al.* (*Science* **248**:975) concluded that Titan is not covered with a deep global ocean of ethane, but that at least some areas of "dry land" are present. Surface temperatures were discussed by McKay *et al.* (*Science* **253**:1118), who considered the roles of both the greenhouse effect and an "antigreenhouse effect" in establishing thermal equilibrium at the surface.

Based on an analysis of the impact delivery of volatiles, Zahnle *et al.* (*Icarus* **95**:1) suggested that the retention of an atmosphere by Titan and the loss of atmospheres from Ganymede and Callisto (which have nearly the same mass and surface gravity) can be understood as the result of higher impact velocities in the jovian system: on the jovian satellites impact erosion dominated, while on Titan the impacting volatiles could largely be retained.

13. TRITON

Data analysis and interpretation from the 1989 Voyager-2 encounter have put Triton in lead place among the satellites for this triennial report. Much of the new work on Triton was published in special issues of *Geophys. Res. Lett.* **17**:1661-1776 (September 1990), *J. Geophys. Res.* **96**:18907-19268 (30 October 1991), and *Icarus* **99**:241-435 (October 1992). Voyager cameras yielded images with better than 1 km resolution; the global color and albedo were analyzed by McEwen (*Geophys. Res. Lett.* **17**:1765), Buratti *et al.* (*J. Geophys. Res.* **96**:19197), Hillier *et al.* (*Science* 250:419 and *J. Geophys. Res.* **96**:19203), and Thompson & Sagan (*Science* **250**:415). The diameter of Triton is 2705 km (Davies *et al. J. Geophys. Res.* **96**:1575), and its relatively high density of about 2.1 is suggestive of a composition about 75% silicate and 25% ice. The cratering history of the satellite was discussed by Strom *et al.* (*Science* **250**:437).

Perhaps the most unexpected discovery of the Triton flyby was the presence of dark plumes or geysers, rising to 8 km above the surface and then carried horizontally for more than 100 km; this discovery was initially described by Soderblom *et al.* (*Science* **250**:4979). The greenhouse effects of surface ices and their possible contribution to the energy source for the plumes were calculated by Brown *et al.* (*Science* **250**:431 and **251**:1465) and Kirk *et al.* (*Science* **250**:424), while an alternative "dust devil" model was suggested by Ingersoll (*Science* **250**:435). The surface energy balance and plume dynamics were further considered by Yelle *et al.* (*Icarus* **89**:34) and Stansberry *et al.* (*Icarus* **99**:242), while evidence for dark streaks and other associated surface features was presented by Hansen *et al.* (*Science* **250**:421). Imaging of clouds and haze in the atmosphere of Triton was described by Rages and Pollack (*Icarus* **99**:289), who concluded that clouds are present at high southern latitudes below 8 km altitude, in addition to a ubiquitous high-altitude haze of submicrometer particles.

Triton's atmospheric photochemistry was discussed by Strobel *et al.* (*Geophys. Res. Lett.* **17**:1729). Ingersoll (*Nature* **344**:315) modeled the atmosphere (primarily nitrogen) in equilibrium with surface frosts and concluded that surface temperature contrasts lead to westward winds at high altitudes. A massive early atmosphere for Triton was considered by Lunine *et al.* (*Icarus* **100**:221), created from the present inventory of volatiles at a time when the satellite was subject to substantial tidal heating. The ionosphere of Triton was the subject of reports by Ip (*Geophys. Res. Lett.* **17**:1713), Yung & Lyons (*Geophys. Res. Lett.* **17**:1717), and Majeed *et al.* (*Geophys. Res. Lett.* **17**:1721). The Triton torus and its interactions with the rest of the neptunian magnetosphere were discussed by Cheng (*Geophys. Res. Lett.* **17**:1669) and Richardson *et al.* (*Geophys. Res. Lett.* **17**:1673)

14. PLANETARY RINGS

Based in part on the extensive Voyager data set for the rings of all four jovian planets, studies of rings and ring dynamics were pursued by many researchers during this triennium. Further analysis of Voyager occultation data by Nicholson *et al.* (*Astron. J.* **100**:1339) has yielded a new absolute radius scale for the Saturn rings, while Shan & Gortz (*Astrophys. J.* **367**:350) have presented an analysis of the radial structure of the B Ring. Rosen *et al.* (*Icarus* **93**:3 and **93**:25) derived resonance structure in the Saturn rings from the Voyager radio occultation data and examined the role of a number of electromagnetic effects on ring structure. Dynamical analysis of Voyager ring data also led Showalter (*Nature* **351**:709) to the discovery of a new satellite of Saturn, named Pan (formerly 1981S13), orbiting within the Encke gap at a distance from Saturn of 133,584 km. Porco (*Science* **253**:995) proposed an explanation for the azimuthal structure in the Neptune rings (the "ring arcs" Adams, Leverrier, and Galle), attributing most of the observed structure to perturbations by the satellite Galatea.

A frequent theme of recent ring research has been the production and evolution of small ring particles that are presumably eroded from larger (often invisible) particles or moonlets. Cuzzi & Durison (*Icarus* **84**:467) studied the effects of bombardment of rings by meteoroids and concluded from calculated dynamical lifetimes that the ages of the C Ring of Saturn and the Alpha and Beta Rings of Uranus are each of order 100 million years. Dones (*Icarus* **92**:194) followed up on the implications of such short timescales and suggested a possible recent origin for the rings of Saturn through tidal disruption of a large comet. Kolvoord *et al.* (*Nature* **345**:695) analyzed periodic features in the F Ring and concluded on dynamical grounds that there must be undiscovered embedded satellites in this ring.

There is increasing interest in the dust rings of low optical depth discovered around each of the outer planets. Grün *et al.* (*Icarus* **99**:191) have reanalyzed all of the Voyager observations of the spokes caused by elevated dust in the B Ring of Saturn and, in contrast with earlier studies, find limited evidence for electromagnetic effects. For the most part the spokes rotate at Keplerian velocities, with an average lifetime of about 100 minutes. Colwell & Esposito (*Icarus* **86**:530; *J. Geophys. Res.* **97**:10227; and *J. Geophys. Res.* **98**:7387) studied the tenuous uranian dust rings discovered by Voyager and concluded that they are formed by micrometeoroid bombardment of unseen moonlet belts made of objects with diameters from about 10 cm to 1 km. They concluded that the small satellites of Uranus and Neptune are fragments or rubble pile agglomerations left over from some older, larger population of satellites. Showalter *et al.* (*Icarus* **94**:451) studied the faint E Ring of Saturn and concluded that the particles in the ring do not follow a power-law size distribution but cluster tightly about a radius of 1 micrometer. Grün (*Rev. Modern Astron.* **4**:157) has written a general review of dust rings around planets, and Showalter addressed similar topics in his paper on dust in planetary ring systems, presented at IAU Colloquium 126.

15. PLANETARY ORIGIN AND EVOLUTION

One of the primary purposes of studying individual planets and satellites is to gain insight into the processes that influence the long-term evolution of the solar system. Many aspects of solar system origin and early evolution are best approached through studies of its most primitive members: comets, asteroids, and meteorites -- all discussed in the report from Commission 15. Here we briefly review the results of cosmogonic research based primarily on the properties of the planets and satellites and upon more general issues of solar system dynamics.

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Rudin & Pollack (*Astrophys. J.* **275**:740) discussed the dynamical evolution of the solar nebula, while Safranov (*Icarus* **94**:260) presented a general review of the formation of the planets in his 1991 Kuiper Prize Lecture. Korycansky *et al.* (*Icarus* **92**:234) discussed current theories for the formation of the giant planets, while Wetherill (*Science* **253**:535) argued for the critical role of impacts in the formation of the terrestrial planets. The survival of protoplanets in the inner solar system is intimately related to the general dynamical evolution of the system, and in particular to the role of Jupiter in modifying the orbits of objects in the inner solar system and in influencing the scattering of high-velocity projectiles from the outer solar system into the region of the terrestrial planets. Slattery *et al.* (*Icarus* **99**:167) modelled giant impacts on the early Uranus in order to explore conditions under which such impacts could produce the present obliquity and rotation period of the planet.

The detailed information now available on the elemental and isotopic compositions of planetary atmospheres offers a rich field for interpretation. Lutz *et al.* (*Icarus* **86**:329) discussed the expected enrichment of deuterium in the primitive ices of the protosolar nebula, in order to understand the observed D/H ratios in planetary atmospheres that may have been derived, at least in part, from these primitive ices. They concluded that D/H of 0.0001 to 0.001 should have been expected. Owen presented a more general review of the significance of deuterium in the solar system in his paper at IAU Colloquium 150. Cruikshank *et al.* (*Icarus* **94**:345) reviewed the evidence for solid C-N bearing material in a variety of primitive solar system bodies, including the D asteroids, comets, the dark side of Iapetus, and the rings of Uranus.

Chyba (*Nature* **343**:129) discussed the formation of planetary atmospheres through the balance between impact delivery of volatiles to the planets and the impact erosion of their atmospheres, showing how the relative importance of these two competing effects depends on planetary mass. Pepin (*Icarus* **97**:2) reviewed the origin and evolution of the atmospheres of the terrestrial planets through the processes of volatile mass fractionation and hydrodynamic escape, in an effort to understand the observed isotopic ratios in the atmospheres of Venus, Earth, and Mars; he also published a comprehensive review of the origin of the noble gases in the terrestrial planets in *Ann. Rev. Earth Planet. Sci.* **20**:389. Hunten (*Icarus* **85**:1) published a general review (in the form of his Kuiper Prize Lecture) of the escape and evolution of planetary and satellite atmospheres, while the Kuiper Prize Lecture by Pollack (*Icarus* **91**:173) discussed the evolution of climates in the terrestrial planets over the age of the solar system. Binzel's Urey Prize Lecture (*Icarus* **100**:274) also concerned physical evolution in the solar system, with emphasis on the smaller bodies. Finally, McKay (*Icarus* **91**:93), in his Urey Prize Lecture, considered issues of planetary evolution and the origin of life.

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