COMMISSION 16: PHYSICAL STUDY OF PLANETS AND SATELLITES
(ETUDE PHYSIQUE DES PLANETES ET SATELLITES)

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1. Introduction

The physical study of planets and satellites is probably one of the more active fields of research of the second half of this century. This is due to space exploration by spacecraft, but also to the use of modern detectors, of large ground-based telescopes, and of powerful computers by active researchers. Planetary research (or planetology) is a pluridisciplinary domain, which requires not only the competence of astronomers, but also of geophysicists, of mineralogists, of climatologists, of biologists, of chemists, of physicists, of "pure" mathematicians, and many other scientists. Many results are at the boundary of those of other commissions such as the 15, 20, 7, 19, 33, 40, 44, 49 and 51 ones. The study of the main results obtained during this last triennum shows a perfect complementarity between space and ground-based observations. It should be arbitrary to separate space and ground-based scientists. They have the same goal and they study the same objects. Quite often, the same individuals use both techniques, depending on the most efficient one for the problem under study. It is remarkable to see that space data collected more than ten years ago are still analysed in connection with ground-based observations. The same remarks can apply for ground-based data. In addition to that, new theoretical models, new numerical simulations and new laboratory experiments have been recently developed. They all contribute to a better understanding of planets and satellites physics.

Two major events took place at the beginning of 1986: the encounter of the Voyager 2 spacecraft with the as yet poorly known Uranus system at the end of January and the flyby of Halley comet by a set of European, Russian, and Japanese spacecrafts at the beginning of Mars. The second event, associated with an unprecedented coordinated ground-based studies, is described in the commission 15 report. Unfortunately, 1987 is the first year for 25 years where no new interplanetary spacecraft was launched in any country of the world and no new planet flyby done.

The explosive increase in the number of published papers on planetary and satellite research has made it impossible to provide an adequate summary of progress in the field over a given three year period in the few pages alloted for this purpose. Just the list of published papers should take much more room. Instead of attempting the customary abbreviated summary, it seemed more appropriate to give just a few examples arbitrarily chosen in order to show how lively, how diverse, and how developed is this field of research. This report is not an exhaustive review of the work done and published between June 1984 and July 1987 in the field of the physics of planets and satellites. It is not even a list of the most remarkable discoveries in this field. Only few results are quoted here as examples, just to show the good health of this field of research.

Most of the information can be found in journals such as Icarus, Space Science Reviews, Astronomy and Astrophysics, Soviet Astronomy, Nature, Science, and many others. More than one hundred books (technical as well as semipopular) have been published in several languages in the field of commission 16. Dozens of meetings have been organized during these past years. Among the proceedings, one can quote: The origin of the Moon (Hartmann, Phillips, and Taylor, editors; NASA Lunar and Planetary Institute, Houston, Texas 77058, 1986), Planetary rings (Greenberg and Brahic editors; The University of Arizona Press, 1984), Protostars and planets II (Black and Matthews editors; The University of Arizona Press, 1985), Saturn (Gehrels and Matthews editors; The University of Arizona Press, 1984), Planets, their origin, interior and atmosphere (Fourteenth advanced course of the Swiss society of astronomy and astrophysics, published by Geneva Observatory, Switzerland, 1984), Physico-chimie de la matière primitive du système solaire (Baglin editor, Société Française des Spécialistes d'Astronomie, Paris, 1986), Space astronomy and solar system exploration (ESA SP 268, 1987). An other source of information can be found in the annual reports of the observatories of all countries.

Every year, the Division for Planetary Sciences of the American Astronomical Society organizes a meeting where the latest results and discoveries are announced. About 400 planetologists of several countries participate to these meetings. They were held in October 1984 in Kona (Hawaii), in October 1985 in Baltimore (Maryland), in November 1986 in Paris (France), and in November 1987 in Pasadena (California). A good source of information can be found in the published abstracts (Bull. Amer. Astron. Soc., respectively vol. 16, p. 621-719, 1984; vol. 17, p. 670-750, 1985; vol. 18, p. 734-834, 1986; vol. 19, p. 795-906, 1987).

2. The origin of the solar system

Several numerical simulations of the evolution of colliding planetesimals have been studied. For example, simulations performed by Wetherill (Science, May 17, 1985) suggest that the terrestrial planets did not grow in an orderly fashion until reaching their present size, but rather are the result of violent collisions between large objects smashing into each other. Some were destroyed by the hammering while others were ejected from the solar system. At the end, only a handful remained intact. If the Wetherill conclusions are correct, this has important consequences on the primordial heating which would have melted the entire terrestrial planets, on the formation of iron-dominated cores and on the removal of primitive atmospheres.

Wetherill and Cox (Icarus 60, 40, 1984 and Icarus 63, 290, 1985) have shown that the two-body approximation is not sufficient to describe terrestrial planets accumulation. Hornung, Pellat, and Barge (Icarus 64, 295, 1985), using appropriate collision operators in a kinetic formalism, have described the thermal velocity equilibrium in the protoplanetary cloud when both gravitational encounters and inelastic impacts are present. Weidenschilling and Davis (Icarus 62, 16, 1985) have shown that orbital resonances can have important effects on accretion in the presence of the gaseous solar nebula.

Noble gases abundance should give a number of information about planets formation. As a first step, Donahue (Icarus 66, 195, 1986) has developed a model for selective loss of noble gases by thermal escape of the gases from planetesimals as they grow to form the terrestrial planets.

Lissauer (Icarus 69, 249, 1987) has presented an unified scenario of planetary accretion in which he gives timescales of formation and details on the structure of the protoplanetary disc.

Cabot, Canuto, Hubickyj, and Pollack (Icarus 69, 387 and 423, 1987) have studied the role of turbulent convection in the primitive solar nebula.

The question of the origin of the excess of ^{26}Mg in the Allende meteorite is still open. After the detection of surprisingly large amounts of radioactive ^{26}Al in the interstellar medium (Mahoney et al., Astrophys. J. 286, 578, 1984), alternatives to the explosion of a nearby supernova just before the formation of the solar system have been explored (Clayton, Astrophys. J. 280, 144, 1984; Cameron, Icarus 60, 416, 1984; Dearborn and Blake, Astrophys. J. Let. 288, 221, 1985). One can wonder if the ^{26}Mg-Al correlation observed in Allende minerals may be a manifestation of a cosmic chemical memory rather than a fossil information about the formation of the solar system.

3. Dynamical studies and chaos in the solar system

Recent discoveries of nonlinear dynamics have open a new and rapidly growing field of research. It is now well-known that the phase space of most Hamiltonian systems is divided: for some initial conditions the trajectories are quasi-periodic, for some others they are chaotic. Even if the solar system is generally perceived as evolving with clockwork regularity, it is just a dynamical system which presents sometimes a chaotic behaviour. There are several physical situations in the solar system where chaotic solutions of Newton's equations play an important role (Hyperion chaotic rotation, orbital history of irregularly shaped satellites, Kirkwood gaps, long term evolution of Pluto orbit, ...). A number of new studies have been recently developed. A review of these problems by Wisdom can be found in Icarus (72, 241, 1987).

4. The inner solar system

A. MERCURY

Observations from Mac Donald Observatory by Potter and Morgan (Science 229, 651, 1985; Icarus 67, 336, 1986) reveal that Mercury is surrounded by a faint atmosphere of sodium and potassium. Doppler shifted narrow emission lines in the spectrum of the planet correspond to 150 000 atoms per cubic centimeter at the planet's surface. This can be compared with the 4 500 helium atoms per cubic centimeter and the mere 8 of hydrogen detected by the 1974 Mariner 10 mission. The sodium comes presumably from minerals sputtered off the surface by the solar wind or from meteoritic dust formed after impacts on the surface rather from internal sources for a planet considered as having outgassed long ago. The Doppler shift of emission lines studied during several months indicates that some of the sodium is moving away from Mercury. Potter and Morgan suspect that Mercury has a tail resembling a comet's ion tail or the sodium torus of Io around Jupiter. Mac Grath, Johnson, and Lanzerotti (Nature 323, 694, 1986) and Smyth (Nature 323, 696, 1986) have discussed the nature and variability of this Mercury's sodium atmosphere.

A set of papers on the physics of Mercury have been published in a special issue of Icarus (71, 335, 1987).

B. VENUS

Astronomers are still reducing the data obtained by the pair of Soviet orbiters of Venus which arrived in October 1983 and which were, among other instruments, equipped with synthetic-aperture radar. The surface below the clouds has been probed between October 1983 and July 1984 and resolved down to about 1.5 kilometer across. The first results were presented at the 16th Lunar and Planetary Science Conference, which was held in Houston in March 1985. Venus seems a planet much more dynamic than Mars, but not more than the Earth. Some regions appear dominated by volcanic activity, others by tectonism. Most of the results have been published in Soviet Astronomy (1985 and 1986).

In mid-June 1985, two balloons were dropped in the atmosphere of Venus by the Vega spacecraft. A network of 20 radio observatories in 10 nations provided around-the-clock tracking of the balloons. Both probes encountered vertical air flows and quickly moving pockets of air. Both probes floatting at the same altitude and at similar latitudes on either side of the equator measured temperatures different by almost 10° Celsius. The results have been described in the March 21, 1986 issue of Science.

The Vega spacecraft also dropped a pair of instrumented landers onto the surface. X-ray fluorescence and gamma-ray spectrometers assessed the surface chemistry and measured relative abundances of the key radioactive isotopes of uranium, thorium, and potassium. Mineral-forming elements like silicon, aluminium, calcium, magnesium, and iron have also been identified.

Rock analyses as well as radar images tend to support the idea that a large part of Venus'surface has been dominated by frequent volcanic outpourings.

Detailed analysis of 1982 and 1985 observation seems to indicate that volcanic basalt covering Venera landing sites contains about 9% iron oxide which is in the form of FeO rather than Fe_2O_3 (Science, December 12, 1986).

Allen and Crawford (Nature 307, 222, 1984; Icarus 69, 221, 1987) have observed Venus at infrared wavelengths with the Anglo-Australian telescope. They were surprised to find rapidly evolving patterns on the dark side of Venus. A careful analysis of the data gives unique information on the temperature, the altitude and the opacity of the clouds responsible for the dark-side patterns. This observation shows that, by the use of polarimetry and spectroscopy, cloud zones can be studied remotely through ground-based observations. This is a good example of complementarity between space and ground-based observations.

An interesting review on Venus' atmospheric dynamics has been written by Golitsyn (Icarus 60, 289, 1984).

C. THE MOON

A conference was held in October 1984 in Kona (Hawaii) on the origin of the Moon. The proceedings have been published in 1986 (Hartmann, Phillips, and Taylor, editors; NASA Lunar and Planetary Institute, Houston, Texas 77058). The origin of the Moon is not yet understood. Each proposed model (intact capture, disintegrative capture, co-accretion, Earth fission or collisional ejection) should be rejected or severely modified on the basis of observed data. The pros and cons of the proposed hypotheses as well as a wealth of lunar science can be found in the proceedings.

In order to overcome most of the difficulties of the classical theories, Cameron (Icarus 62, 319, 1985) and Benz, Slattery, and Cameron (Icarus 66, 515, 1986) have developed numerical simulations on the formation of the Moon as the result of a single collision between a Mars-sized body and the proto-Earth.

D. MARS

A set of papers on the evolution of the climate and the atmosphere of Mars has been collected in a special issue of Icarus (71, 201, 1987).

New image processing techniques are now applied to the data obtained during the Viking mission and a number of new physical studies of Mars have been performed these last years. For example, Grant and Schultz (Science, August 21, 1987) explain the formation of regions marked with an array of puzzling dark, filamentary streaks by local, intense atmospheric phenomena such as strong vortex of tornadic intensity. Such tornado-like phenomena scratch the surface of Mars.

Another example is given by Lucchitta (Science 235, 565, 1987). His analysis of Viking images seems to indicate volcanic activity on Mars more recently that accepted until now. He has made a recent survey of the troughs in Valles Marineris which reveals dark patches that are interpreted to be volcanic vents. Their configuration and association with tectonic structures suggest that they are of internal origin. Their albedo and color index indicate mafic composition. Morphologic details and low albedo suggest they are young and perhaps recent.

Wind is the primary agent shaping the surface of Mars today. Greeley and colleagues have used a special wind tunnel at the NASA-Ames Research Center in order to simulate martian conditions. They have compared their results to Viking observations. It seems that Mars has a scarcity of normal sand. Sand-size particles exist on Mars, but as clumps of particles breaking apart after striking a target rather than single grains.

Owen, Maillard, de Bergh, and Lutz (Science, 1988; Bull. Amer. Astron. Soc. 19, 817, 1987) have detected from CFH Observatory HDO in the infrared spectrum of Mars and have obtained the first measurement of the D/H ratio on Mars. It is six times larger than the D/H ratio in Earth oceans. This enrichment over the telluric value implies a much more rapid escape of Hydrogen from Mars in the past, consistent with a denser and warmer atmosphere than the one we find there today. If this scenario is correct, liquid water could have existed in the past. This could explain the existence of channels cut by slowly running water.

5. The outer solar system

In 1986, the Voyager's January 24 flyby has completely changed our knowledge on the planet and its surroundings. It is interesting to compare the speculations on Uranus and its satellites as they were discussed at the A.A.S.-D.P.S. Baltimore meeting in October 1985 (Bull. Amer. Astron. Soc. 17, 685-745, 1985) with the data sent by the spacecraft. Most of the results can be found in Science (233, 1-132, 1986), in the 1986 and 1987 Icarus issues, and in the proceedings of the A.A.S.-D.P.S. meetings (Paris 1986 and Pasadena 1987) and of the A.G.U. meetings. It can be said that most of that we now know about Uranus and its satellites was transmitted to Earth during just a few days in late January 1986. The enormous quantity of data returned was such that astronomers have yet to work through it all. Analysis of Voyager 2's investigation of the Uranian system will take many years.

A. PLANETARY RINGS

(a) The discovery of Neptunian ringlike arcs

The four giant planets of the solar system are now known to possess ring systems which are all very different from the others. The discovery of Neptunian rings is a remarkable result of international cooperation and of observations organized by the universities of Paris (Brahic, Sicardy et al.) and Tucson (Hubbard et al.). Collaborating teams of French and American astronomers, observing stellar occultations by Neptune from ground-based telescopes (ESO, CFHT, IRTF, CTIO, ...) have simultaneously recorded in the close vicinity of Neptune a short reduction in the intensity of the star's light from different sites in 1984 and in 1985. Seven isolated events are also reported out of about one hundred observations. When the observation shows an event, nobody has ever seen any evidence for a second occultation, as would be expected from a uniform, complete ring around the planet. This discovery is due to Brahic, Hubbard, Nicholson, Sicardy, Vilas and colleagues (Nature 319, 636, 1985; Bull. Amer. Astron. Soc. 18, 778, 1986 and 19, 885, 1987). Neptune seems surrounded by ringlike arcs of material. More information should be obtained in August 1989 during the close flyby by Voyager 2 spacecraft. In order to understand the structure of Neptunian arcs, an intensive campaign of ground-based coordinated observations should be organized.

An upper limit of 0.006 for the normal optical depth of an hypothetical continuous disc of dark matter around Neptune has been given, from observations of ground-based stellar occultations, by Sicardy, Roques, Brahic, Bouchet, Maillard, and Perrier (Nature 320, 729, 1986).

(b) The discovery of Jupiter's gossamer ring

A reexamination of the Voyager images by Showalter, Burns, Cuzzi and Pollack (Nature 316, 526, 1985; Icarus 69, 458, 1987) has yielded a refined understanding of Jupiter's diffuse ring system. The system is composed of a relatively bright narrow ring (about 7 000 kilometer wide) and inner toroidal halo (about 20 000 kilometer full thickness) with an exterior "gossamer" ring and without the previously suspected inner ring.

(c) Uranus' rings

The Voyager 2 flyby confirmed the existence of the planet's narrow, dark ring system discovered in 1977 and continuously observed since from ground-based observatories by stellar occultation techniques. The results are reported in a series of articles in Science (233, 1-132, 1986). They confirm the picture given by ground-based observations, but they also provide a large number of new details and unexpected features. New rings, new small satellites near the rings, and previously unknown fine structure within the rings have been discovered. Images of two additional rings (1986U1R and 1986U2R) have been taken, the first one is narrow and orbits between the two outermost of the classical rings, and the second one is broad and closer to the planet than any other known ring. Stellar occultations by the rings seem to reveal possible additional rings and partial rings. One single long-exposure image obtained at very high phase angle shows a very unexpected view of the rings, the micrometer-sized particles form a complex system with the nine classical rings all discernible but not dominant in brigthness. Radio occultation experiment indicates a distribution of particles in the external epsilon ring that is almost devoid of particle sizes in the one-to-ten-centimeter size range. Ring particles have an extremely low albedo, possibly as the result of methane ice bombardment by high energy protons moving in the Uranus' magnetosphere. During the Voyager crossing of the Uranus ring plane at about 4.5 Uranian radii, up to 40 micro-particle impacts per second have been recorded by the antenna of the spacecraft.

A very impressive check of the theory of ring confinement by satellites has been done by Goldreich and Porco (Astron. J. 93, 724 and 730, 1987). 1986U7 and 1986U8 are the inner and outer shepherds for the epsilon ring. 1986U7 is the outer shepherd for the delta ring. 1986U8 is the inner shepherd for the gamma ring.

(d) Saturn's rings

The data acquired by Voyager experiments such as imaging science, radio science, ultraviolet spectrometer, and photopolarimeter are still the object of intensive studies. A large diversity of phenomena has been discovered. For example the eccentric Saturnian ringlets at 1.29 Saturnian radii and at 1.45 Saturnian radii have been studied in detail by Porco, Nicholson, Borderies, Danielson, Goldreich, Holberg, and Lane (Icarus 60, 1, 1984). The kinematics of the first one seems determined solely by its interaction with Titan. The kinematics of the second one seems determined solely by Saturn's nonspherical gravity field. Porco, Danielson, Goldreich, Holberg, and Lane (Icarus 60, 17, 1984) have studied the outer edges of Saturn's A and B rings. The dynamics of the A-ring edge seems driven by the coorbital satellites through complex processes. The shape and the dynamics of the B-ring edge are primarily determined by its proximity to the Mimas 2:1 resonance. In unperturbed regions, the B-ring's vertical thickness is of the order of 10 meters.

(e) Ring dynamics. The confinement of planetary rings

Ring dynamics seem to be driven by nearby satellites. Several extensive studies of this complex phenomenon have been performed and much remain to be done. For example, Meyer-Vernet and Sicardy (Icarus 69, 157, 1987) have discussed the physics of resonant disc-satellite interaction. Petit and Hénon (Icarus 66, 536, 1986) have systematically studied satellite encounters in order to understand gravitational interactions between particles in planetary rings.

Shukman (Sov. Astron. 28, 574, 1984) has obtained a kinetic equation having a collisional term allowing for both frontal and tangential inelasticity, and taking into account the spin of the particles. He has investigated the dynamics of Saturn's rings using this equation. Lissauer (Nature 318, 544, 1985), Goldreich, Tremaine, and Borderies (Astron. J. 92, 490, 1986), Lin, Papaloizou, and Ruden (Mon. Not. R. Astron. Soc. 227, 75, 1987), Sicardy (Bull. Amer. Astron. Soc. 19, 891, 1987) have studied the confinement of planetary arcs.

B. ATMOSPHERES OF GIANT PLANETS

(a) The abundance of Hydrogen and Helium in the atmosphere of giant planets

The measurement of the relative abundance of hydrogen and helium in the atmosphere of giant planets can be considered as one of the great discoveries of solar system studies. Before the Voyager encounter with Uranus, the discrepancy of He/H ratios between Jupiter and Saturn was not well understood. Helium cannot be mixed with metallic hydrogen inside Saturn where the temperature is not high enough. As a consequence, there is a relative deficiency of helium relative to hydrogen in the atmosphere of Saturn. The relatively low value measured in 1979 for Jupiter (of the order of 24% per mass unit) corresponded to the solar value and, thus, to a still smaller value in the Big Bang if there were no separation of hydrogen and helium inside Jupiter. This was evidently a problem. The measurement of the relative abundance of helium and hydrogen in the atmosphere of Uranus gives the answer. The value which has been found lies between 26% and 27% and is in perfect agreement with new solar models (Conrath, Gautier, Hanel, Lindal, and Marten, J. Geophys. Res., 1987; Phil. Trans. Roy. Soc. London, 1987; Bull. Amer. Astron. Soc., 1986, 1987). This value suggests that helium differentiation has not occurred on Uranus. Comparisons with values previously obtained for Jupiter and Saturn imply that migration of helium toward the core began long ago on Saturn and may also have recently begun on Jupiter. This means that the relative amount of helium in the primitive solar nebula which gave birth to the solar system is given by the values measured in the Sun and in the atmosphere of Uranus. This result is in good agreement with galactic chemical models which include a substantial decrease in deuterium during the evolutionary process. About 3% of helium has been produced between the Big Bang and the formation of the solar system. In addition, the comparison of atmospheric compositions of giant planets permits a test of formation scenarios. Present available data do not definitively exclude the gas instability model, but are consistent with nucleation models.

(b) The Deuterium to Hydrogen ratio

Bézard, Drossart, Maillard, Tarrago, Lacome, Poussigue, Lévy, and Guelachvilli (Bull. Amer. Astron. Soc. 19, 849, 1987) have measured a value of 1.6×10^{-5} of the D/H ratio in Saturn's atmosphere. This confirms two other determinations of the D/H ratio from the molecule CH_3D. This result is three times larger than the determination in the visible range from HD molecules. This conflict between the two values is not yet solved.

(c) Water and sulfur abundances in the atmosphere of Jupiter

The Jupiter's atmospheric transmission windows at 2.7 microns and 5 microns have been observed from the Kuiper Airborne Observatory. Results are reported by Larson, Davis, Hofmann and Bjoraker (Icarus 60,621, 1984) and by Bjoraker, Larson and Kunde (Icarus 66, 579, 1986 and Astrophys. J., 1986).

The 2.7 micron observations suggest that photolytic reactions in Jupiter's lower troposphere may not be as significant as was previously thought. It seems that, contrary to expectations, sulfur-bearing chromosphores are not present in significant amounts in Jupiter's visible clouds. The global abundance of sulfur in Jupiter may be significantly depleted. The apparent absence of hydrogen sulfide is troublesome for chemists and theorists, who had generally counted on sulfur to explain some of Jupiter's colors. Phosphorus-bearing condensates or organic polymers are now primary candidates for explaining Jupiter's visible coloration.

The 5 microns observations are a very diagnostic observational tool to probe the troposphere of Jupiter. Abundances of NH_3, PH_3, CH_4, CH_3D, CO and GeH_4 have been measured in the 1- to 6-bar pressure range in Jupiter's troposphere. The observed abundances of CO, GeH_4, and PH_3 are consistent with models of convective transport from Jupiter's deep atmosphere. There is much less water in the atmosphere of Jupiter than expected unless narrow moist convective plumes in the lower troposphere of Jupiter can reconcile the apparent depletion of water with a near-solar abundance of oxygen throughout the interior (Lunine and Hunten, Icarus 69, 566, 1987).

(d) Jupiter and Neptune ground-based images

Some of the best images ever taken of Jupiter have recently been obtained by Lecacheux, Laques and colleagues at the Pic du Midi Observatory (1987). They are particularly useful in the frame of the International Jupiter Watch before the launch of the Galileo mission.

High quality images of Neptune have been taken at Mauna Kea Observatory by Hammel and Buie during the summer 1987. The Neptune clouds rotation period lies between 17 and 18 hours and varies probably with latitude. The images reveal bright cloud features in Neptune's southern hemisphere, but no one in the northern hemisphere contrary to the images obtained by Smith and Terrile in 1983. Neptune's atmosphere seems to change with time.

(e) Chemical and dynamical studies of Jupiter's and Saturn's atmospheres

Ingersoll and Miller (Icarus 65, 370, 1986) have studied large-scale motions in the atmospheres of Jupiter and Saturn. Mac Low and Ingersoll (Icarus 65, 353, 1986) have studied the time-dependent behaviour of spots in the Jovian atmosphere. Their main result concerns the time-dependent behaviour of interacting spots. Mergings are the most frequent type of interaction. They are irreversible, and do not resemble the interaction of two solitary waves. Spots also spontaneously eject and absorb material.

Appleby and Hogan (Icarus 59, 336, 1984) have developed radiative-convective equilibrium models for Jupiter and Saturn in a study centered primarily on the stratospheric energy balance and the possible role of aerosol heating. Comparisons with Voyager data and results indicate that a dust-free model (no aerosol heating) furnishes a good mean thermal profile for the Jupiter's stratosphere, but cannot be ruled out at low latitude on Jupiter. It seems that aerosol heating played a minor role at the time of the Voyager 2 encounter in Saturn's midlatitude stratospheric energy balance. Other possibilities are discussed in the paper quoted above.

A major problem encountered in the study of the predominantly hydrogen atmospheres of the giant planets is the degree to which thermal equilibration occurs between the para and ortho states of Hydrogen molecules. Infrared spectra obtained by the Voyager spacecraft indicate that the para hydrogen fraction near the 300-mbar pressure level on Jupiter is not in thermodynamic equilibrium. The implications have been recently analysed by Conrath and Gierasch (Icarus 57, 184, 1984).

Bézard, Drossart, Maillard, Tarrago, Lacome, Poussigue, Lévy, Guelachvilli, Noll, Geballe, Knacke, and Tokunaga (Bull. Amer. Astron. Soc. 19, 849, 1987) have detected germane GeH_4 with the same concentration in the atmosphere of Jupiter and Saturn.

(f) Uranus' atmosphere

In addition to the measurements of the helium to hydrogen ratio, many fundamental data have been obtained during the flyby of Uranus by Voyager 2. Astronomers are far to have reduce all the data. We give here only few examples of the discoveries (Science 233, 1, 1986). Uranus has a methane cloud deck with a base near the 1.2-bar pressure level. Near the cloud base, the methane to hydrogen ratio is about 0.02, this corresponds to 20 times the carbon abundance seen in the Sun. Only a few discrete cloud features were seen in images, with prograde zonal wind speeds ranging from 0 near the latitude of - 20° to about 200 m/s near the latitude of - 60° and 0 again at the south pole. Near Uranus' equator, retrograde winds with speeds near 100 m/s are observed. There is a temperature inversion in the Uranus' stratosphere. The temperature rises from a minimum of about 52K at a pressure level of 0.1 bar to about 70K at 0.001 bar. In the extreme upper atmosphere, there is a very large hydrogen scale height with an associated temperature of the order of 800K and significant drag forces on orbiting ring particles. The expected auroras have not been found on Uranus, but ultraviolet emissions from sunlit portions of the very extended atmosphere show a process, which is not yet fully understood, called "electroglow".

A seasonal model of Uranus' atmosphere has been studied as a function of time, i.e. as a function of the phase angle with the Sun (Bézard and Gautier, Bull. Amer. Astron. Soc. 1987; Friedson and Ingersoll, Icarus 69, 135, 1987). The radiative transfer of an hydrogen and helium atmosphere with minor constituents such as methane ands acetylene is calculated. Thanks to the heat redistribution by the winds, the temperature suffers very little variations in the troposphere and slightly larger variations in the stratosphere. The results are in good agreement with Voyager data. The colder the planet, the longer it takes to warm it. The Uranus' dark pole "has kept the memory" of the time it was directly exposed to solar light. But the expected temperature drop at the equatorial level is not observed.

C. INTERNAL STRUCTURE OF GIANT PLANETS

The heat balance of Uranus has just been measured (Pearl, Conrath, Hanel and Pirraglia, Bull. Amer. Astron. Soc. 19, 852, 1987) from Voyager infrared spectrometer observations. Contrary to Jupiter and Saturn which have important internal sources of energy (Jupiter has still "some memory" of its primordial heat and helium is falling down in the metallic hydrogen inside Saturn), Uranus has a very weak internal source (a maximum excess of 9% has been measured) which could be explained by natural radioactivity or by a remnant of accretion heating.

The rotation period of Uranus clouds has been measured from Voyager images. It varies as a function of latitude from 14.2 hours at -70° to 16.9 hours at -27°. The rotation period near -40° is about 16.0 hours. Left-hand polarized signals from the planet show a periodicity of 17.24 (+/- 0.01) hours, which presumably corresponds to the rotation period of Uranus interior (Science 233, 1, 1986). The Uranus magnetic field is probably a consequence of the rotation of an interior ocean of ionized material. Its structure is unexpected. It is tilted 59° with respect to the rotation axis and offset from the center of Uranus by 0.3 Uranian radius. The strength of the dipole moment is intermediate between Saturn's and Earth's.

A remarkable reference book on "Planetary Interiors" has been published by Hubbard (Van Nostrand Reinhold Company, New York, 1984). A stimulating review on giant planets' interior models has been recently made by Stevenson (Icarus 62, 4, 1985). Podolak, Young, and Reynolds (Icarus 63, 266, 1985; Icarus 70, 31, 1987) have studied models in order to understand the differences between Uranus and Neptune interior structures. Internal structure of satellites has also been studied. For example, Zharkov, Leontjev, and Kozenko (Icarus 61, 92, 1985) have discussed models, figures, and gravitational moments of the Galilean satellites of Jupiter and icy satellites of Saturn.

Planetary rings can act as probes of the internal structure of the planet they surround. For example Marley, Hubbard, and Porco (Bull. Amer. Astron. Soc. 19, 889, 1987) have studied Saturnian radial p-mode oscillations and C-ring structure. Correlations between ring features and specific oscillation modes may help constrain interior models. Observation of a central flash during a stellar occultation by Neptune (Brahic, Sicardy, Roques, Mac Laren, and Hubbard, Bull. Amer. Astron. Soc. 18, 778, 1986) allows a determination of Neptune's oblateness.

D. SATELLITES OF GIANT PLANETS

(a) Io

The remarkable volcanic eruptions of Jupiter's satellite Io continue to be studied several years after their discovery in 1979. Much of the new material which has been recently published derives from the Voyager images and other data, but significant new material has been obtained from ground-based telescopic studies. In particular, Johnson, Morrison, Matson, Veeder, Brown and Nelson have observed the infrared flux simultaneously at 8.7, 10, and 20 microns (Science 226, 134, 1984). They have been able to measure the infrared emission from volcanic hotspots on Io's surface as a function of longitude. They have found that volcanic hotspots are not distributed uniformly in longitude and that most of the heat from Io's volcanic interior escapes through a relatively small number of major volcanic centers. These data suggest that the active volcanic regions observed by the Voyager spacecrafts are still active, particularly the region around the feature known as Loki. A second major emitting region corresponds probably to Pelé. The actual global average heat flow from Io has still to be measured. Any estimate depends on the assumptions introduced in a model.

(b) Ganymede

Kirk and Stevenson (Icarus 69, 91, 1987) have developed thermal models of Ganymede's interior, assuming a mostly differentiated initial state of a water ocean overlying a rock layer. They have discussed implications for surface features. Zuber and Parmentier (Icarus 60, 200, 1984) have performed a geometric analysis of Ganymede's surface deformations in order to study its tectonic evolution: while lateral motion cannot be ruled out, it may not be required to explain the geometry of the system. The tectonic features of Ganymede have also been studied by Golombek and Banerdt (Icarus 68, 252, 1986) and by Bianchi, Casacchia, Lanciano, Pozio, and Strom (Icarus 67, 237, 1986).

(c) Mutual events of Jupiter's moons

From May 1985 to Avril 1986, the Earth and Sun lied very near the Jupiter's equatorial plane. A campaign of observations of the mutual eclipses and occultations of the satellites have been organized all over the world in order to determine the orbits of Jupiter's moons with unprecedented precision (K. Aksnes and F. Franklin, Icarus 60, 180, 1984). Data reduction still continues.

(d) Titan

Titan, Saturn's largest satellite, is surrounded by a substantial atmosphere which has been probed by the infrared, the ultraviolet and the radio instruments of the Voyager 1 spacecraft. The analysis of the Voyager results continues. An interesting example is the study of the composition of the layers of clouds and haze by W.R. Thompson and C. Sagan (Icarus 60, 236, 1984). Incorporating the temperature and pressure data from Voyager observations and the absorption and emission characteristics of important atmospheric gases, they have obtained a model atmosphere of Titan which includes nitrogen, argon, methane, a cloud layer of methane droplets, and tholin hazes. They have derived quantitative estimates of the amount of liquid methane and organic solids in the clouds and the haze. Deuterium to hydrogen ratio and the origin of Titan's atmosphere have been discussed by Pinto, Lunine, Kim, and Yung (Nature 319, 388, 1986). For the first time, HCN has been detected at radio wavelengths in Titan (Coustenis, Bézard, Gautier, Marten, Samuelson, Bull. Amer; astron. Soc., 19, 873, 1987) and CO at millimeter wavelengths (Marten, Gautier, Lecacheux, Rosolen, Paubert, Bull. Amer. Astron. Soc., 19, 873, 1987). The amount of CO detected by this method differs by a factor 10 with the amount of CO detected in the infrared range. These observational results are not yet interpreted. Millimeter emission lines are formed in Titan stratosphere while infrared emission lines are formed in Titan troposphere. Thus, all photo-chemical models of Titan's atmosphere (which assume that CO is uniformly distributed) are no more valid.

(e) Hyperion

As a consequence of its out-of-round shape, its large orbital eccentricity and its tidally evolved rotation, Hyperion tumbles irregularly (Wisdom, Peale, and

Mignard, Icarus 58, 137, 1984). Its period of rotation as well as the direction of its rotation axis changes constantly on a chaotic manner.

(f) Uranus' satellites

Ten new satellites orbiting Uranus between the rings and the orbit of Miranda have been discovered by the Voyager's cameras (Science 233, 1, 1986). Their diameter ranges from 40 kilometers to 170 kilometers. The disc of 1985U1 and of the five classical satellites has been resolved and high resolution images have been obtained. The masses of the five classical satellites have been measured and thus the density are now known: Miranda (1.24 +/- 0.31), Ariel (1.55 +/- 0.23), Umbriel (1.58 +/- 0.23), Titania (1.68 +/- 0.07), and Oberon (1.64 +/- 0.06). The albedos ranges from 0.07 for 1985U1 to 0.40 for Ariel. Umbriel is particularly dark (albedo of 0.19) and the geologic activity seems to increase when the distance to Uranus decreases. There is very little evidence for geologic activity on the surface of Oberon. Titania, the largest Uranian satellite, has a surprising number of fractures across its surface. Ariel possesses a remarkably fractured surface with some indication of ice flow across parts of the surface. Miranda, the smallest of the major Uranian satellites, shows a surprising high degree and large diversity of tectonic activity. Half of its surface is relatively bland, old, cratered terrain. The remainder comprises three large regions of younger terrains, each rectangular to ovoid in plan, that display complex sets of parallel and intersecting scarps and ridges as well as numerous outcrops of bright and dark materials.

The cratering record of Uranus' satellites, studied by Strom (Icarus 70, 517, *1987), shows two different populations of different ages. In this paper, the solar* system cratering record from Mercury to Uranus is rewieved. It seems very complex and any proposed origin of the impacting objects must be considered highly speculative at present time. Mobilization of cryogenic ice in outer solar system satellites has been discussed by Stevenson and Lunine (Nature 323, 46, 1986).

(g) Triton

Cruikshank (Bull. Amer. Astron. Soc. 19, 858, 1987; with Apt, Icarus 58, 306, 1984; with Brown and Clark, Icarus 58, 293, 1984) has detected liquid nitrogen on the surface of Triton. Delitsky and Thompson (Icarus 70, 354, 1987) have suggested that Triton's surface could be partially covered with a soup of liquid nitrogen and methane on which floats some organic compounds including liquid ethane C_2H_6. Lunine and Stevenson (Nature 317, 238, 1985) have discussed the physical state of volatiles on the surface of Triton and have concluded that a nitrogen ocean cannot be excluded, but requires very restrictive assumptions.

E. PLUTO - CHARON

Nearing perihelion in 1989, Pluto is actually closer than Neptune to the Sun. Consequently the planet should be near its highest temperature and astronomers have good observation conditions. It turns out that the plane of Charon's highly inclined orbit is now sweeping across the inner solar system, allowing us to see, thanks to Pluto's slow orbital motion, from 1985 to 1990, a rare series of occultations and transits of the planet and its moon. These events, which only occur every 124 years, have made it possible to determine the basic physical *parameters such as the radius, the albedo and the mean density of the planet and* the satellite. A major fraction of rocky material seems to lie inside Pluto. Mutual-event data have been combined with speckle interferometer measurements. Tedesco, Buratti, Binzel and Tholen have described the results in Science (1985). The total mass of the couple Pluto-Charon is no more than about two-thousandth that of the Earth, much more than previous estimates. It turns out that Charon is the largest satellite with respect to its parent planet in the solar system.

Spectroscopic evidence has suggested that Pluto possesses an atmosphere. The surface layer of solid methane gives rise to an atmosphere, but the vertical extent and the thermal properties of this gaseous layer are still unknown. From data collected by the infrared IRAS satellite, Sykes, Cutri, Lebofsky, and Binzel (Science, 1986) have developped a model in which Pluto's poles are capped by methane ice. An equatorial band extending from about - 45° to + 45° in latitude should be free of methane ice. In this model, Pluto's atmosphere, sublimed from the ice, should be about 1000 times less dense than the Earth atmosphere at sea level. Marcialis (Bull. Amer. Astron. Soc. 19, 859, 1987) has observed Charon occultation by Pluto in the near infrared range. Substraction of fluxes measured before, during and after the event has yielded individual spectral signatures for each body. Charon's surface appears extremely depleted in methane compared to Pluto and water frost has been identified at the surface of Charon.

The origin of the couple Pluto-Charon is still discussed. Lyttleton suggested in 1936 that Pluto was once a Neptunian moon ejected after a gravitational encounter with Triton which reversed the direction of Triton's orbital path. MacKinnon (Nature, September 27, 1984) has rejected this hypothesis: the presently accepted masses of Triton and the Pluto-Charon system could not have changed Triton's orbital direction and momentum conservation would have ejected Pluto-Charon not only from the Neptune system, but from the solar system as well. Mac Kinnon proposes that both Pluto and Charon began as large, independent outer solar system planetesimals rotating around the Sun.

6. Laboratory experiments

To understand the abundance of elements and the chemical reactions in planetary atmospheres, molecule spectra have been studied as a function of physical conditions: for example, one can quote laboratory studies of phosphine photolysis in the atmosphere of Jupiter and Saturn by Ferris and Khwaja (Icarus 62, 415, 1985) and laboratory studies of reactions between chlorine, sulfur dioxide, and oxygen by DeMore, Ming-Taun Leu, Smith, and Yung. To understand the initial stages of planets and satellites formation and cratering observations, collisions between various material have been studied. For example, Lange and Ahrens (Icarus 69, 506, 1987) have performed impact experiments in low-temperature ice. Fujiwara (Icarus 70, 536, 1987) has studied the energy partition into transverse and rotational motions in catastrophic disruptions by impact.

7. Other planetary systems?

Extrasolar planetary science begins to be an active (and up to now) speculative field of research. With new detectors, astronomers are intensively scanning the surroundings of nearby stars in order to discover extrasolar planets (see commission 51 report). In spite of premature announcements, no one has been still discovered (until autumn 1987), but the first observations reveal much more dark matter than expected in the immediate vicinity of a number of stars. This has may be nothing to do with any stage of planet evolution, but it is interesting to see that material is available around several stars. The answer to the question of the existence a large number of extrasolar planets is linked on to our understanding of planet formation. Anomalous long-wavelength infrared radiation has been found by the infrared satellite IRAS from Vega and other stars. Observations from the Kuiper Airborne Observatory have confirmed this discovery (Science and Nature, 1984). The best interpretation is that these stars are surrounded by a shell or a ring of solid bodies. Blocking the bright light from the star itself and using state-of-the-art imaging and processing techniques, Smith and Terrile have taken a photograph in visible light of the disc surrounding the star Beta Pictoris and seen edge-on (Science, 1985). Zuckermann and Becklin have discovered an infrared excess around a nearby white dwarf (Bull. Amer. Astron. Soc., 1987).

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