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

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1. INTRODUCTION

This report includes a number of achievements in planetary science in the last approximately three years. Each section was contributed by the scientists identified at the end of that section.

2. MERCURY

The discovery of radar bright regions at high latitudes on Mercury by ground-based observations with the combination of the Goldstone and VLA facilities has reminded planetary scientists that little is known about this planet. These radar-bright signatures are similar in character to the radar-bright regions observed at the poles of Mars and from locations on the Galilean satellites that were observed nearly ten years ago and attributed to coherent backscatter in a transparent medium with embedded scattering centers. For Mercury both water ice and elemental sulfur have been proposed for the transparent medium. Both have an extremely small complex dielectric coefficient for cm wavelengths and therefore both are transparent to radar. Volatility and transport studies show that water ice and sulfur are likely to be stable in permanently shadowed regions with sulfur stable in mostly shadowed regions at higher temperatures than water ice.

More imaging of Mercury's sodium (Na) and potassium (K) atmosphere with an image stabilizer at the McMath-Pierce Solar telescope has confirmed that sometimes the Na and K appear in isolated regions as bright spots, and sometimes in N-S symmetric pairs. Further, Na and K have been observed as bright spots at about the same location during the same observing period. The cause of this morphology remains a mystery but four source mechanisms have been proposed: 1. daytime diffusion of Na and K out of terrain that was saturated by implanted ions on the night side, 2. diffusion of Na and K out of well-fractured regions (perhaps basins) possibly composed of materials with compositions enhanced in Na and K (e.g., alkali-rich feldspars), 3. heavy ion sputtering of Na and K from surface materials by ions focused in the cusps of Mercury's magnetic field, 4. unspecified solar wind effects. A recent analysis of systematic high-resolution spectroscopic measurements of Na from 1985-1990 show a strong diurnal variation with abundances in morning and at noon a factor of several over late afternoon.

Advances have been made in determining the composition of Mercury's surface. Until a few years ago, Mercury's regolith could be described as rocky, slightly "bluer" than the Moon, and largely lacking in the 0.9-1 μm absorption band associated with FeO absorption. In the past three years, microwave measurements at 2, 5, 10 and 20 cm, combined with radiative and conductive models, have established that Mercury's regolith is a factor of two more transparent than lunar soils. This can be explained by unusually low FeO or TiO_2. Medium-resolution mid-IR spectroscopic observations of Mercury's surface show a strong signature of plagioclase feldspar at equatorial regions near 120 degrees mercurian longitude. Assuming that the spectrum is indeed that of plagioclase feldspar, the location of the emissivity maxima

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in the spectra indicates that the modal abundance of the Na-rich end-member, albite, is between 10 and 40% at that location. It remains to be determined the extent to which the rock composition and the Na and K atmosphere are coupled, but this discovery of a relatively Na-rich mineralic material is suggestive of a causal relationship.

Contributed by Ann L. Sprague, Lunar and Planetary Laboratory, University of Arizona

3. VENUS

Through analysis of radar images and measurements of the radiophysical properties of Venus obtained by the Magellan mission, significant progress in understanding the general character of the geological history of Venus for the last 300-500 million years was achieved. In the beginning of this morphologically recognizable time period and intensive global or nearly global tectonic deformation occurred that led to the formation of the so-called tessera terrain. This was followed by several global episodes of basaltic volcanism, alternating with pulses of moderate regional to global tectonic deformation, thus forming the majority of the presently observed venusian plains. These two stages together lasted for a few tens to a hundred million years. Then, endogenic activity on Venus decreased significantly, resulting primarly in the formation of rift zones and rift-associated basaltic volcanism. Exogenic activity was of very low intensity through all this period of time.

Data on the gravity field of Venus obtained by Doppler tracking of the Magellan spacecraft were processed and made available to the planetary science community. A study of the correlation between the gravity and the long-wave topography showed that the planet's surface can be generally divided into two parts. The majority (about 90% of the surface) shows evidence that the long-wave topography is mostly caused by the planet's mantle convection, indicating that the planet is now endogenically active. The remainder of the surface consists of crustal plateaus, represented by the tessera terrain. Their long-wave topography is controlled not by mantle convection, but by crustal isostasy. For these areas the thickness of the planet's crust is estimated at 25 to 40 km. Earth-like models of Venus' interior were developed and thoroughly analyzed in view of the constraints imposed by the Magellan data.

Venus' cloud-top jet patterns are correlated with the cold collar and overall wind system, as defined on the basis of Venera 15 infrared observations. A refined evaluation of the radiative transfer of thermal radiation in the lower Venus atmosphere was carried out using a more accurate approximation of the SO_2 gas opacity, as well as the phase matrix of aerosols in the clouds and its spectral dependence in the wavelength range 2-40 μm. Modeling of the thermochemical equilibrium for the deep (1-3 km) atmosphere of Venus, and climatic changes for the first 0.5 Gyr, was undertaken for a closed gaseous system consisting of *H-C-N-O-S*. The model predicts initial climatic stability, followed by great climatic changes during the resurfacing events.

Contributed by A. T. Basilevsky, Vernadsky Institute, Moscow, M. Ya. Marov, Institute of Applied Mathematics, Moscow and V. N. Zharkov, Schmitt Institute of Earth Physics, Moscow

4. MARS

The past few years have seen numerous exciting achievements in the study of Mars, with the focus on Earth-based remote sensing observations and continued analysis of previous spacecraft data on the mineralogy of the surface and the composition of the atmosphere. Specifically, advances include the identification of a new, much older Martian meteorite and continued detailed mineralogic, petrologic, and geochemical studies of the other SNC meteorites; new insights on aspects of the Martian atmosphere related to the general circulation, photochemistry, isotopic geochemistry, the physical and radiative properties of dust and other aerosols, and the evolution of the early Martian climate; and new interpretations on the geology and geophysics of past and present Mars from continued study of Viking and Mariner data. This time period has also seen the advancement of key scientific issues related to Mars exobiology; in fact, in a fundamental change in philosophy, an exobiologic strategy for the future exploration of Mars has been embraced and accepted by the community.

Because of the devastating loss of the Mars Observer spacecraft in August 1993, ground-based and Earth-orbital telescopic observations have provided the only new remote sensing data of Mars over the past few years. These new data include UV spectra and near-UV to near-IR images by the repaired Hubble Space Telescope, revealing the extremely cold and cloudy nature of the aphelic atmosphere at unprecedented spatial resolution. Also during this time the first high spatial resolution ground-based near-

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IR (MKO/IRTF) and mid-IR (Palomar) imaging spectroscopic observations were obtained, allowing the mapping of compositional variations among Mars atmospheric volatiles and of mineralogic variations associated with silicate and other spectral features. Additional remote sensing studies included high spectral resolution infrared (IRTF, Catalina) and millimeter-wave (IRAM, VLA) observations of Mars' atmospheric water vapor, showing large interannual and latitudinal variations; high spectral resolution infrared observations (KPNO) of atmospheric C-, O-, and H-bearing species and their isotopic ratios, providing new limits on trace atmospheric constituents like HCl and H_2CO; and the first measurements of Mars atmospheric He (EUVE), providing constraints on atmospheric loss and planetary outgassing processes.

Continued analysis of the near-IR imaging spectroscopic observations returned by the Phobos-2 ISM instrument had led to the refinement of airborne dust physical and optical properties, new constraints on the surface ferric and ferrous iron mineralogy, and the tentative identification of spatially-variable Mars atmospheric water vapor anomalies. Data from the Phobos-2 Termoskan IR instrument have been used to constrain the thermal inertia of ejecta blankets and other surface geologic units. Viking Orbiter IRTM observations were used to construct new maps of the albedo and thermal inertia of the Martian polar regions and to assess the role of atmospheric dust in altering the apparent surface thermal inertia. Re-calibration of some of the Mariner 6 and 7 IRS spectra (parts of which remain unique in their spatial and spectral coverage) has led to new findings on the possible presence of carbonate minerals on the Martian surface as well as the surprising finding of extremely coarse-grained (mm to cm-sized) CO_2 ice deposits in the south polar cap. Re-analysis of some of the Viking IRTM polar temperature data indicates that this coarse-grained ice anneals into "glaze ice" during the polar night, forming highly transparent sheets of ice, possibly more than a meter thick.

The Mars origin of the SNC meteorites is now widely accepted by informed investigators. The excellent match between the Mars atmospheric composition and the composition of trapped gases in one of the SNCs, confirmed by several laboratories, provided the convincing evidence.

The Martian meteorite, ALH84001 was found to have an Ar-Ar isotopic age of 4 Gyr–more than three times the age of the other identified SNCs. This newly-identified Martian meteorite may, with further analysis, provide an absolute age chronology for Noachian terrains on Mars. It may also confirm that the late heavy bombardment was a pervasive inner solar system event, and thus crater counting chronologies can in fact be extrapolated from the Earth-Moon system to the other terrestrial planets.

A series of discoveries about ALH84001 has raised the issue of life on Mars to a high level in the attention of planetary scientists and biologists. The meteorite contains carbonate globules in fractures, in association with clusters of elongated shapes no more than 100 nanometers in length. The investigators who announced the discovery of the elongated structures noted their similarity to the earliest terrestrial microfossils. The investigators also noted that the dark rims of the carbonate globules contain magnetite and FeS suggestive of a biological synthesis on early Mars. The discovery of polycyclic aromatic hydrocarbons associated with the carbonate structures adds strength to the case for the biological interpretation of the material found in the meteorite. The further study of ALH84001 is certain to command the attention of many investigators for the next several years.

Measurements of D/H in hydrated minerals within the SNCs, provide constraints on the extent of atmospheric H loss with time, and indicate that there has likely been extensive recycling of water (thus possibly an active early Martian hydrosphere) between the crust and atmosphere over the course of Martian history.

New studies of the Martian atmosphere include refinements to general circulation models to more accurately simulate observed atmospheric pressure and temperature variations, atmospheric dynamics, and surface aeolian features; determinations of more accurate physical and optical properties of suspended atmospheric dust from spacecraft observations and numerical simulations, used to more accurately model the radiative effect of suspended dust on the atmospheric circulation and climate; and new models of Martian photochemistry, atmospheric escape processes, and isotopic fractionation, all of which provide constraints on the origin and evolution of the Martian atmosphere. In particular, much emphasis has been placed on understanding the history and evolution of the Martian climate from theoretical studies of recently-recognized quasi-periodic obliquity changes, from detailed modeling of the role of long-term sputtering loss to space on the evolution of the Martian climate, and from a re-analysis of the frequency and magnitude of historic dust storm activity.

Climate models based on the early Sun and the role of CO_2 cloud condensation suggest that an early "warm and wet" Martian climate could not have been maintained with just a thicker CO_2 atmosphere but instead would have required additional greenhouse gases (like SO_2) or dust to maintain the higher temperatures. The early Martian climate may have been primarily cold and dry, punctuated by brief periods of warm, wet conditions only in the first billion years of Mars history. The magnitude and duration of these warm, wet climatic periods are unknown, but given the probable obliquity history of the planet, and morphologic evidence for near-surface water preserved in valley networks and rampart craters, there is still some optimism that environments conducive to the formation of life may once have existed on Mars.

Studies of Martian geology have also concentrated on determining the evolution of the past climate through an understanding of the role of water, wind, volcanism, and impacts in shaping the observed geomorphology. These studies include the identification of possible glacial and coastline landforms, paleolakes, subsurface ice, and evaporite deposits in Viking Orbiter images; assessment of the amount of atmospheric volatiles released during ancient and more recent volcanic events; mapping of possible hydrothermal alteration zones associated with impact (e.g., Hellas) and tectonic (e.g., Valles Marineris) features; and analyses of dust deposits and dune fields with an emphasis on determining the current and past wind regimes. Advances in Mars geophysics have primarily centered around new gravity modeling results derived from a re-examination of Mariner and Viking data.

These results indicate that the north-south hemispheric dichotomy is likely the result of an offset between Mars' centers of gravity and figure, rather than a fundamental feature of the shape of Mars or related to a specific geologic boundary. Models for the origin of the hemispheric dichotomy must now be reassessed in light of this result.

Contributed by James F. Bell III (Cornell University)

5. SPECTROSCOPY OF PLANETARY ATMOSPHERES

The major achievements of the last few years through high-resolution spectroscopy of planetary atmospheres concern, among other topics, the first studies of the very tenuous atmospheres around small bodies like Pluto and Io, a better knowledge of some regions of Venus and Mars that had not previously been well investigated, the detection of minor compounds in the atmosphere of Neptune that completely change our view on its origin and evolution, the detection of a new organic species in the atmosphere of Titan that reveal the high degree of complexity of the organic chemistry presently at work on Titan. In addition, high-resolution spectroscopy has allowed us to study some of the modifications induced in the atmosphere of Jupiter by the collision of comet Shoemaker-Levy 9.

Most of the studies presented here have been made in the infrared or in the millimetric range using the best ground-based facilities available (IRTF, UKIRT, CFHT, ESO 3.6 m telescope, IRAM, JCMT) or the Kuiper Airborne Observatory. Some have also been obtained from UV spectroscopy with the Hubble Space Telescope.

Our view of the atmosphere of Io has been revolutionized recently thanks to ground-based millimetric observations, complemented by HST observations. In the last few years, the spatial distribution of gaseous SO_2 has been thoroughly studied and SO was detected. The SO_2 observations could be explained by an atmosphere in hydrostatic equilibrium covering only a very small portion of the satellite, if the atmosphere is very hot in the first scale height, which seems very unlikely. Another hypothesis, which is currently being investigated, is that the atmosphere of SO_2 is an irregular volcanic atmosphere in permanent fast motion.

Methane was detected in the atmosphere of Pluto by near-infrared spectroscopy. It is the first detection of any atmospheric gas on this planet. Curiously enough, the CH_4 abundance derived indicates that, although N_2 frost must be the main frost surface constituent, there must be areas of almost pure CH_4 frost on the surface.

The exploration of the deep atmosphere of Venus by ground-based near-infrared spectroscopy was continued. Recent work has shown, in particular, that the atmosphere of Venus is very dry down to the surface of the planet. Additional information was obtained on two sulfur compounds, SO_2 and OCS, providing very valuable insight on the sulfur chemistry in this atmosphere. New information on the upper atmospheres of Mars and Venus concerns the general circulation within these atmospheres which has been probed by looking at the Dopper shift and shape of CO lines. The study of emissions of O_2 that are very highly variable with time and location on the planet also brings a new view on some very active local chemical or dynamical processes that occur in the atmosphere of Venus around 90-100 km altitude.

On Titan, a new molecule, CH_3CN was detected. Three nitriles had been seen by Voyager (HCN, C_2N_2 and HC_3N). This new species is found to be about 300 times less abundant than HCN. Although it was predicted to be present on Titan from laboratory simulations of organic chemistry, it had never been included in photochemical models. The exact chemical pathways leading to its production on Titan remain to be determined.

CO and HCN were detected on Neptune, in contradiction to current thermochemical models. They were not found on Uranus, however. Their detection on Neptune may imply that the conversion from CO to CH_4 and from N_2 to NH_3 occurs only partially in the deep atmosphere of Neptune. Their absence on Uranus would then be due to the low level of the internal source of energy.

High-resolution spectroscopy has also been used to study the compositional and temperature modifications induced by the fragments of comet SL-9 when they hit Jupiter in July 1994. Emissions by several locally enhanced atmospheric constituents (CO, CH_4, NH_3, C_2H_2, C_2H_4) or new created compounds (HCN, S_2, CS and CS_2) were observed and, whenever possible, monitored, providing very interesting information on impact-induced shock chemistry, dynamics of the plumes and photochemistry in the strongly altered jovian stratosphere.

Contributed by C. deBergh, Observatoire de Paris

6. JUPITER: COMET IMPACT, AURORA, AND SATELLITES

Activity in the field of Jupiter science was dominated by the study of the collision of comet Shoemaker Levy 9 (SL9) with Jupiter in July 1994. Possibly the largest, most concentrated observing campaign ever undertaken for an astronomical event was focussed on the unprecedented collision of more than 20 fragments of the tidally disrupted comet SL9 with Jupiter. The fragments impacted the atmosphere near 45 degrees south latitude creating large visible debris patterns and a variety of other perturbations to the atmosphere. Observable effects lingered in the atmosphere for up to one year after the collisions.

The initially large and disparate data recorded by many observers have been mostly reduced and published and some synthesis of the events has occurred. A good understanding of the observed lightcurves at multiple wavelengths has emerged. For many events, the impact is first marked by a short, relatively weak brightening close to the predicted impact time and probably caused by the bolide as the fragment enters the atmosphere. A second short, weak brightening occurs soon after and is attributed to the rising fireball. Several minutes later an intense brightening occurs at infrared wavelengths as material falling back from the initial impact rapidly heats the atmosphere. It is this so-called main event, the supersonic re-impact over a very wide area of debris blasted out from the initial impact that produced the most widespread effects in Jupiter's atmosphere.

Many molecules and atoms never before seen in Jupiter were observed in the aftermath of the collisions. Emission from Mg, Na, Ca, Fe, Si, and Li were all observed in visible and UV spectra and almost certainly represent debris deposited in the atmosphere by the comet. Several sulfur-containing species, S_2, CS_2, and CS were observed as well. H_2O and CO were both observed, with CO the most abundant of any of the molecules observed after the impacts. Observations of line shapes and strengths shows that the material was generally high in Jupiter's stratosphere, at pressures mostly below 1 mbar. There is also evidence for vertical layering with some species such as NH_3 lying deeper than 1 mbar. Attempts to reproduce the observed mix of molecules with thermochemical models have been only partially successful.

Tracking of visible debris after the impacts provided a means of probing winds at altitudes well above Jupiter's visible cloudtops. The evolution of the impact sites shows that zonal winds decrease with altitude above the cloudtops. Discrete cycolonic and anticyclonic circulation patterns extend into Jupiter's lower stratosphere where they perturbed the evolution of the impact debris. Observations of Jupiter's clouds with HST show that zonal winds have remained constant compared to Voyager data.

The most remarkable effect related to the debris, a wave of condensation that moved outward from several large impact sites at a rate of 450 m/s may be an expression of a gravity wave trapped in a stable layer in Jupiter's troposphere. However, this explanation requires a large enhancement in the abundance of water in Jupiter.

A major advance in the understanding of jovian aurorae and Jupiter's magnetic field has been made by the detailed mapping of auroral emissions of H_3^+ (infrared) and H_2 (UV). Mapping of the main auroral oval appeared to show that the peak auroral emission was poleward of the field lines connected to Io, that is, from farther out in Jupiter's magnetosphere. The detection of the Io footprint in WFPC UV images some 4 to 6 degrees equatorward of the main auroral oval confirms this conclusion and should allow a refinement of models of Jupiter's magnetic field. Fainter emission extends on both sides of the main oval and bright knots poleward of the main oval are highly variable. The global perspective offered by ongoing observations will complement the limited, but much higher resolution, observations being made by the Galileo spacecraft.

Atomic oxygen was detected near Jupiter's satellite Europa at ultraviolet wavelengths with a ratio of line strengths indicative of electron impact dissociation of molecular oxygen. This observation was used to infer the presence of a tenuous molecular oxygen atmosphere around Europa with a surface pressure of 10^{-11} bars.

Two weak bands of molecular oxygen were detected in the visible wavelength spectrum of Ganymede. The band strength varies and is strongest on the trailing hemisphere, suggesting a causal connection with magnetospheric ions that preferentially impact the trailing hemisphere. The formation of these bands depends on an interaction between two O_2 molecules and is normally present only in the solid or liquid state or high pressure gas. Oxygen molecules trapped in small voids in the surface ice may be responsible for these bands. Ultraviolet spectra obtained with the HST show a broad absorption from the Hartley band of ozone at 260 nm. The band is shifted and broadened compared to the gas phase ozone band, both effects consistent with trapping of ozone in small voids as also inferred for O_2. Both observations suggest that Ganymede must also have a tenuous oxygen atmosphere.

Contributed by Keith S. Noll, Space Telescope Science Institute, and Glenn S. Orton, Jet Propulsion Laboratory

7. JUPITER: THE GALILEO PROBE MISSION

The Galileo spacecraft, which arrived at Jupiter on December 7, 1995, consisted of two main components: an atmospheric entry probe and a planetary orbiter. The probe plunged into the atmosphere of Jupiter on December 7, 1995, accomplishing the first direct sampling of the atmosphere of one of the outer giant planets and surviving the most difficult atmospheric entry ever attempted. On the same date the orbiter was the first ever to be placed in orbit about Jupiter, and began a 22-month tour of the jovian system.

The Galileo probe entered the jovian atmosphere at 47.4 km/sec. It was necessary to take advantage of Jupiter's rotational velocity in order to reduce the relative entry speed into the atmosphere, otherwise the probe would have entered at nearly 60 km/sec, an entry speed it could not have survived. The probe had to enter the atmosphere on a flight path that was 8.5 degrees inclined to the horizontal. An error of 1.5 degrees too shallow and the probe would have skipped out of the atmosphere, 1.5 degrees too steep and the probe would have been destroyed.

Once in the atmosphere, the probe slowed from 47.4 km/sec to less than Mach 1 in less than two minutes. This deceleration caused the probe to experience 228g. Due to the high speed entry a shock layer was set up in Jupiter's atmosphere that was located about 3 cm from the nose of the probe. The temperature in the shock layer reached 14,000 C. The probe survived because of its protective heat shield, which was a carbon phenolic material. About half the weight of the probe was associated with the forward heat shield, and approximately two-thirds of it was ablated away during entry.

Knowledge of the global context of the probe entry site is an important factor bearing directly on how probe results are interpreted. Due to technical problems with the tape recorder onboard the Galileo orbiter, planned approach images of the probe entry site from the orbiter camera had to be canceled. An HST image from October was compared with an infrared false color image taken from the Infrared Telescope Facility (IRTF) in Hawaii at nearly the same time. The cloud patterns at the probe entry site on December 7, were determined based on IRTF images taken in November and December. The probe entered near the southern boundary of what is known as a 5 μm hotspot, so called because they are bright near the 5 μm part of the infrared spectrum. Such hotspots cover only about 15% of the surface area near the equator of Jupiter, and are thought to be clearings in the clouds.

The probe found that Jupiter's main constituents, H and He, are very nearly in the same proportion that they were in the Sun when it was first forming out of a gas and dust cloud, about 28% He by mass. Jupiter, by mass, consists of nearly 24% He. This is a picture of Jupiter that is significantly different from that previously formulated. Prior to the Galileo mission, remote sensing estimates in 1979 from the flyby Voyager spacecraft indicated that the jovian *He* abundance by mass was 18%, considerably less than in the early Sun. Saturn has only about a quarter of the *He* abundance by mass in its atmosphere that Jupiter does, implying that Jupiter and Saturn have evolved along different paths.

Galileo found that *C* and *S* have greater relative abundances to hydrogen on Jupiter than they do in the Sun, by about a factor of 2-3 (the abundance of *N* in the form of ammonia has not yet been determined). However *O*, in the form of water, is apparently scarce on Jupiter, at least where the Galileo probe entered. This is very different from expectations, in which it was anticipated that thick water ice clouds would be encountered by the Galileo probe. The greater abundances of *C* and other heavier elements on Jupiter as compared to the Sun imply that comets and other small bodies have impacted Jupiter over the age of the Solar System and deposited extra material. However, it is hard to understand why such impacts would not also have brought in water (hence *O*).

One of the main objectives of the Galileo probe was to measure winds in the jovian atmosphere. From pictures of Jupiter taken by spacecraft and by Earth based telescopes, it was known that at cloud levels winds blew mostly in the east-west direction and reached speeds of greater than 100 m/s. Recent measurements from HST indicated narrow jets at the probe entry latitude, moving in the same direction Jupiter rotates and reaching speeds of about 150-170 m/s. It was not known if these winds extended to significant depths below the clouds. The Galileo probe encountered winds exceeding 180 m/s, and showed that the winds extend deep below the visible clouds on Jupiter. It is not known exactly how the winds on Jupiter are produced, but the probe provided evidence that energy escaping from the very hot interior of Jupiter is the ultimate energy source.

The Galileo probe also measured the temperature-pressure relationship in the jovian atmosphere. Temperature and pressure increase with depth with a funtional dependence very close to adiabatic. The probe radioed signals to the orbiter from a depth where the pressure was about 24 bars. The temperature at that point was about 150 C. At the point where the probe first starting taking direct measurements, the pressure was about 0.4 bars and the temperature was -140 C. In the upper atmosphere acceleometers determined atmospheric density from the deceleration of the probe, from which temperature and pressure could be deduced. It was found that the atmosphere higher than about 300 km above the one bar pressure level is hundreds of degrees hotter than expected, reaching temperatures exceeding 900 C.

The probe started direct measurements near the bottom of the top cloud layer, and detected the mostly ammonia ice particles by measuring how sunlight was diminished as the probe went through this top cloud. The probe also detected a second tenuous cloud with the nephelometer, probably consisting of ammonium hydrosulfide ice particles, although the composition has not yet been definitely identified. This cloud was very tenuous by Earth standards, and had a visiblility within it of about 2 km. But below this, no thick water clouds were detected in contrast to what was anticipated before the mission. This lack of detection of deep water ice clouds is consistent with the fact that there was little water vapor measured in the atmosphere.

The Voyager spacecraft which had flown by Jupiter in 1979 detected lightning events as they took pictures of the night side of Jupiter. Most of this lightning occurred near 45-50 N latitude. The Galileo probe was equipped with optical sensors to detect nearby lightning flashes, however the probe did not detect any lightning optically. It did pick up radio signals emitted by distant lightning bolts. The conclusion is that Jupiter has less frequent lightning than the Earth on a per unit area basis, but individual lightning bolts are about 10 times more energetic than on Earth.

The Galileo Probe also searched for organic compounds. Complex organic compounds were not observed at concentrations sufficiently above the limit of detectability of the probe instruments to be identified.

Before it hit the atmosphere, the probe measured high-energy charged particles trapped in Jupiter's magnetic field. These "radiation belts" are analogous to the Van Allen radiation belts which exist above the Earth's atmosphere. New radiation belts consisting of helium and heavier ions were discovered that extended to within 0.4 jovian radii of the cloud tops.

Contributed by Richard E. Young, NASA Ames Research Center

8. SATURN: ATMOSPHERE AND INTERIOR

Several significant events have motivated recent efforts to improve our understanding of the origin, structure, and evolution of Saturn and the other giant planets. The launch of Hubble Space Telescope provided enhanced spatial and frequency resolution relative to the International Ultraviolet Explorer and ground-based facilities. This facility has been used to define the major equatorial storm which occurred in 1990, the third of a series spaced 57 years apart; to record subsequent minor convective activity in 1994; to verify the stability of the hexagonal wave pattern north of 70 deg; and to better understand the haze properties and the relation of dayglow and auroral emissions to solar activity.

Failure of the Galileo Probe to detected a substantial ammonia cloud bottom near 0.7 bars has been attributed to the fact that the probe entered a region of enhanced 5 μm emission, hence a region relatively free of ammonia clouds. This explanation does not fully explain the lack of a deeper water cloud. These results have significant implications for the structure and evolution of Saturn as well as Jupiter.

Detection of brown dwarfs and extrasolar-system planets is providing additional constraints for models to investigate internal structure and evolution of giant planets, and the anticipated launch and opportunities that will be provided by the Cassini mission are motivating significant international collaborations to better understand the Saturnian interior, troposphere and stratosphere.

Interior models that include atmospheric radiative transport and cooling, when compared with conventional fully convective models, yield shorter cooling times and generate conditions favorable to H-He phase separation. Galileo abundance ratios and continuing analysis of trace species in Saturn's atmosphere will influence interpretation of these efforts as well as our understanding of the fraction of C, N and O and the role that icy planetesimals played in formation of the outer planets.

Efforts to better define radiative transport rates and stability of the atmosphere have led to acquisition of an improved absorption spectrum by use of direct spectrophotometry. These results have been compared with limited cold temperature laboratory measurements to obtain realistic gas opacities. A second effect that can influence the atmospheric structure and stability is conversion of ortho-para H. Recent work indicates that after the onset of a convective event the relaxation of the ortho/para-H toward dynamic equilibrium drives the atmosphere toward stability and in the case of Saturn, and Uranus to a greater degree, could account for intermittent convection.

Many of the gross differences in the high resolution visible aspects of the atmospheres of Jupiter and Saturn are due to differing amounts of stratospheric and tropospheric hazes. Formation of fresh ammonia clouds are readily visible in the Jovian atmosphere, while convective activity in Saturn's atmosphere is limited to sporadic convection and convective overshoot. Hubble Space Telescope has been utilized to better understand the equatorially concentrated tropospheric and polar stratospheric hazes. Relative color differences of the belt-zone structure appear largely due to latitudinal variation of the size distribution of tropospheric aerosols.

Contributed by Reta Beebe, New Mexico State University

9. SATURN: RINGS AND SATELLITES

On three occasions during a year-long period, the Earth passed through Saturn's ring plane: 22 May 1995, 10 August 1995, and 12 February 1996. On 19 November 1995, the ring-plane swept across the Sun. During the Earth crossings, the rings are viewed edge-on from Earth. These ring plane crossing events were viewed widely with the Hubble Space Telescope and numerous ground-based telescopes to study the planet, its satellites, and the rings themselves. The observed time of minimum ring light corresponds to the time of ring-plane crossing. By comparing these observed times with ring-plane crossing times and independent knowledge of Saturn's pole position at one epoch (such as from the analysis of the 28 Sgr occultation in July 1989, and others), the rate of precession of Saturn's pole can be measured. May crossing data led to a precession rate that is 65% of the predicted rate (due to direct solar torque and solar torque on satellites transferred to Saturn). However, the August data were more ambiguous, with crossing times differing for the east and west ring ansae.

The amount of signal at the ring-plane crossing leads directly to the vertical extent of the rings. Both May and August data indicate a vertical thickness of 1.2 - 1.5 km, consistent with an earlier determination of this value from the 1980 Saturn ring-plane crossing. Other methods indicate that the main rings should be much thinner, on the order of 200 m or less; the F ring may be contributing most or all of the vertical thickness. A surprise during the ring-plane crossing was the first Earth-based images of Saturn's tenuous G ring, with the finding that this ring is neutral in color. The blue color of the E ring was confirmed. The linking of this ring with Enceladus as origin is strengthened by the observed increase in brightness at the orbital radius of Enceladus, and a lack of correlation with any other satellites.

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Observations immediately before the August ring-plane crossing measured the spatial distribution of OH molecules forming a tenuous ring. The number density of these molecules decreases with height above the ring-plane, and increases with increasing distance from Saturn along the ring-plane, implying the presence of a toroidal OH cloud enveloping the rings, with maximum density outside the main rings. These observations will aid in understanding the lifetimes of ring atmosphere neutrals.

Some of the small inner satellites have not been seen since the Voyager encounters with Saturn in 1980 and 1981 and therefore their ephemeris accuracy was unknown. During the May ring-plane crossing, and confirmed during the August ring-plane crossing, Prometheus was found to be 20 degrees behind its predicted location, a discrepancy several orders of magnitude larger than the predicted uncertainty. The cause of this discrepancy is unknown. Atlas was also found to be discrepant, leading its predicted location by 25 degrees, which is marginally consistent with its expected orbital uncertainty.

Attempts were made to locate previously unseen satellites while the rings were near minimum brightness. Several candidates were found, but most are believed to be short-lived clumps of dust within the F ring.

The long time-span around this ring-plane crossing season provided opportunities to observe eclipses, occultations, and mutual events of and by the satellites. From the timing of these events, more precise orbital information is obtained than can be achieved through direct imaging. These data will aid in the refinement of satellite ephemerides.

Contributed by Amanda S. Bosh, Lowell Observatory

10. COMPOSITIONS OF PLUTO, CHARON, TRITON, AND THE CENTAUR OBJECTS

Near-infrared spectroscopy (1-2.5 μm) of small bodies in the outer solar system continues to yield information on the surface compositions of these objects.

Pluto's surface consists mostly of ice, dominated by N_2, with CH_4, CO, and H_2O. Methane occurs in two forms on Pluto; some CH_4 is frozen in solid N_2 (1-2% by mass), while some pure CH_4 lies on the surface. The CO may be frozen into the N_2 matrix. H_2O probably occurs as spatially isolated regions. Regions of low albedo (as seen in Hubble Space Telescope images) are probably covered with organic matter, as yet unidentified, and with no detected spectral features. Pluto's tenuous atmosphere is primarly N_2, but CH_4 has been detected. Charon's surface shows absorptions of H_2O ice, but other ices and refractory solids may exist.

Triton is spectrally similar to Pluto, with its icy surface dominated by N_2, CH_4, CO, CO_2, and H_2O. All of the methane on Triton appears to be dissolved in N_2; there is no evidence of isolated CH_4. The ^{13}C isotope in CO is clearly detected. Because of its very low volatility, CO_2 probably occurs in spatially isolated patches, as does H_2O. Triton's tenuous atmosphere is primarly N_2.

Two bodies termed Centaur objects have been studied spectroscopically (0.4-2.5 μm). These objects are important because they are dynamically new (10^6 to 10^7 years) to the planetary region of the solar system, and they probably originated in the Kuiper Disk. Object 5145 Pholus has a very red reflectance in photovisual region, H_2O ice bands in near-IR, and a strong absorption band at 2.27 μm attributed to combinations in C-H bands in organic solids, probably light hydrocarbons (e.g., methanol, hexamethylenetetramine). The object 2060 Chiron exhibits neutral reflectance with no discernible spectral features. It shows episodic cometary activity and CO emission.

Contributed by D. P. Cruikshank, NASA Ames Research Center and T. C. Owen, University of Hawaii

11. THE KUIPER BELT

In the past few years, the Kuiper Belt has made the transition from a speculative theoretical component of the solar system to an observationally established entity. The primary trigger for this advance was the application of large-format charge-coupled device (CCD) detectors on ground-based telescopes. As of summer 1996, 36 trans-Neptunian objects have been unambiguously identified and 21 of these have been observed at more than one opposition. In parallel with the observational effort, a number of exciting theoretical developments are helping to understand the dynamical structure and planetary significance of the trans-Neptunian region.

The Kuiper Belt population numbers 70,000 objects (diameters > 100 km) in the 30 to 50 AU radius zone. This is 2 to 3 orders of magnitude larger than the population of comparably sized main-belt asteroids. With the measured inverse cube size distribution, the total mass may approach 0.1 Earth masses. The size distribution is compatible with recent impact models in which shattering collisions generate small objects (later to appear in the inner solar system as comets) from larger ones. The Kuiper Belt may also be a significant source of dust, with collisional dust production rates that rival or exceed the dust supply to the Zodiacal Cloud.

The ground-based observations show that 35% of the trans-Neptunians have semi-major axes near 39.4 AU. This corresponds to the 3:2 mean-motion resonance with Neptune, and draws a parallel with Pluto, which occupies the same dynamical niche. The hitherto unrecognized family of "Plutinos" numbers 30,000 objects larger than 100 km in diameter. Several Plutinos (1993 SB, 1994 TB, 1995 HM5, and 1995 QY9) have perihelia inside the orbit of Neptune, strengthening the dynamical similarity with Pluto. In addition, a single object (1995 DA2) has been identified in the 4:3 resonance at 36.3 AU.

These observations raise the question of how so many bodies could be trapped in the 3:2 resonance. Malhotra's resonant-trapping theory postulates that trapping occurred in Neptune's growth phase, when angular momentum exchange with the surrounding planetesimal disk led to net radial migration. The theory makes specific predictions for the relative populations of different resonances, and is amenable to observational tests. An exciting possibility is that measurement of the relative populations of different resonances will allow a determination of the timescale for the formation of Neptune and the ejection of the Oort Cloud. We now recognize Pluto as the largest of the known Kuiper Belt objects. Pluto's composition (see the comments by Cruikshank and Owen in this Report) and the presence of its tidally locked satellite may or may not further distinguish this object from other Kuiper Belt bodies, as future studies will reveal.

Physical measurements of the Kuiper Belt objects are especially challenging because of their great distance and faintness. Observations at the Keck 10 m telescope show that the Kuiper Belt objects exhibit a surprising and not well understood spectral diversity. Kuiper Belt objects may possess a wide range of initial compositions, as do their counterparts in the main-belt. Alternatively, collisional resurfacing may cause the observed diversity in optical colors. This unexpected and exciting new area of planetary research promises to reveal much about the conditions of planetesimal formation, the origin of comets, and may even relate to the regenerated dust disks present around main-sequence stars such as Beta Pictoris.

Contributed by David Jewitt, University of Hawaii

12. HST OBSERVATIONS OF THE KUIPER BELT

While it was ground-based observations which first proved the existence of the Kuiper Belt (starting with the discovery of 1992 QB1 by Jewitt and Luu), the connection between the Kuiper Belt and Jupiter family comets was still uncertain. The 35+ objects found with ground-based searches range in size from 50-200 km (radius). Known short-period comets are of order a few to 10 km in radius. The Centaur objects, such as Chiron and Pholus, thought to be transitional objects between the Kuiper Belt and the short-period comets, are of sizes similar to the population of Kuiper Belt objects which have been found from the ground. Thus, the questions arise how to substantially reduce the size of objects during the transition from the Kuiper Belt to the inner solar system, if large objects are typical of Kuiper Belt objects, or where is the missing population of the small Kuiper Belt objects?

To help answer these questions, the Hubble Space Telescope was used during cycle 4 for a "pencil beam" survey of the Kuiper Belt to very faint limiting magnitudes. The objects detected with ground-based telescopes typically have V magnitudes from 21.5 to 24.5. Assuming "cometary" albedos of 0.04, it would be necessary to image to V magnitudes of 28.5 to detect comet-sized objects in the Kuiper Belt.

The team of Cochran, Levison, Duncan and Stern used the HST to search a single field of the ecliptic on two occasions for 5 hours each time. The incidence of radiation events and the narrow PSF of the HST necessitated a non-traditional search method which consisted of assuming Kuiper Belt orbits, shifting and co-adding and performing an automated search. These results were then compared statistically with non-realistic orbit searches in order to determine if there were objects detected in excess of the noise.

The first HST deep images were analyzed by assuming 3:2 resonant orbits; the statistical analysis revealed approximately 40 excess objects with inclinations within 12 degrees of the ecliptic. These objects were found in the magnitude range of 27.5 to 28.6, or in sizes from 5 to 10 km, assuming an albedo of 0.04.

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Since the results are statistical in nature and specific orbits cannot be determined, these results have been met with some (understandable) skepticism. Accordingly, the team tried to duplicate the results with a second field with the HST in February 1996. Unfortunately, increased noise in the background of the images lowered the signal/noise of the observations and thus, the limiting magnitude. The limiting magnitude of this second field was approximately V=27.6, or at the magnitude of the brightest objects found in the first field. Thus, no objects in excess of the noise were detected. This is consistent with the results of the analysis of the first field but hardly constitute satisfactory or convincing proof that the first results are robust.

Verification of the detection of cometary-sized objects in the Kuiper Belt awaits further HST Cycle 6 observations. Those observations should produce higher signal/noise detections of the brighter small objects and statistically detections of still smaller objects. Work with the archive will also be commenced in order to extend the areal coverage of the very deep survey.

Contributed by Anita L. Cochran, University of Texas

13. PLANET FORMATION

Current models of solar system formation hypothesize that the terrestrial planets and the cores of the gas giant planets were formed by the mutual accretion of solid planetesimals. Planetesimals in the inner solar system were made primarily of rocky material (including metals), whereas those farther from the Sun also contained ices. Most planetesimal growth models attempt to reproduce the configuration of planets observed in our solar system, but the ultimate goal is to understand the physical processes involved well enough to model a diverse range of possible planetary configurations. Important issues for the general problem of planetary growth include the formation of protoplanetary disks, the growth of kilometer-size planetesimals from dust, the accretion of gas by giant planet cores, and dispersal of protoplanetary disks.

Dynamical simulations have been quite successful in reproducing the basic configuration of the inner solar system, and jovian resonances may be able to account for the asteroid belt. Analogous simulations are less successful in the outer solar system, because the combination of high escape velocities from giant planet surfaces and low heliocentric orbit velocities allow gravitational scatterings to produce much more eccentric planetary orbits than are observed. However, by adding an artificially enhanced gas drag, which promotes temporary capture into exterior mean motion resonances with Jupiter, the accretion of Saturn's solid core can be simulated. A more realistic eccentricity damping mechanism for large planetesimals in the outer solar system may have been self-excited disk torques in the solar nebula.

Two explanations have recently been proposed to explain the origin of Pluto's pecular orbit. If the jovian planets suffered a substantial orbital migration as a result of planetesimal scattering, Neptune could have captured Pluto into the 3:2 orbital resonance and pumped up its eccentricity to its current value. Alternatively, gravitational interactions with the current jovian planets can temporarily capture Pluto into the 3:2 orbital resonance with Neptune, but a dissipative event, such as the giant impact that presumably formed Charon or gravitational interactions with small bodies in the Kuiper Belt, is required to damp Pluto's libration amplitude and thereby stabilize its resonant orbit. A more complete review of recent developments concerning the dynamical aspects of planetary growth is provided by Stewart and Lissauer in the Celestial Mechanics (Commission 7) section of this year's IAU reports.

Contributed by Glen R. Stewart, University of Colorado, and Jack J. Lissauer, State University of New York, Stony Brook