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The planets beyond Jupiter

INTRODUCTION

At large heliocentric distances, the giant planets of the Solar system – Jupiter, Saturn, Uranus and Neptune – have specific characteristics: with respect to the terrestrial planets, they have a large size, a low density, a fast rotation period around their axis; they also all have a ring system and a large number of satellites. The two brightest of them, Jupiter and Saturn, have been known since Antiquity. In contrast Uranus and Neptune, which are both smaller and farther away from the Sun, have been discovered relatively recently: Uranus was first observed by William Herschel in 1781, following the new developments of large telescopes, while the discovery of Neptune, by John Adams and Urbain Le Verrier in 1846, was the direct result of celestial mechanics calculations.

Both Jupiter and Saturn have been monitored from ground-based telescopes for over three centuries, after Galileo Galilei, in 1610, turned to the sky his newly built refractor and discovered, in particular, the four satellites of Jupiter later called galilean. Concerning the two major giant planets, we thus have a huge data base, first made of drawings, then completed with photographs and spectra. The first images revealed the latitudinal structure of belts and zones on both planets, the existence of the Great Red Spot on Jupiter, and the nature of Saturn's ring system. Photographs of improving quality provided a monitoring of the planets' meteorological features, showing, in particular, the stability of the Great Red Spot on Jupiter but the variability of the other smaller features. The development of ground-based spectroscopy, first in the visible, then in the infrared range, provided a quantitative information about the chemical composition of Jupiter and Saturn. Methane and ammonia were detected in 1932, and hydrogen, the main constituent of the giant planets, was observed for the first time in 1960. In the 1970s, the improvement of infrared spectroscopy techniques, coupled with the use of larger and larger ground-based telescopes, led to the discovery of a long list of minor atmospheric constituents, on both Jupiter and Saturn. We thus had already a good knowledge of the nature and composition of their atmospheres when the first spacecraft devoted to the exploration of the giant planets, Pioneer 10 and 11, were launched in 1972 and 1973 respectively.

Uranus and Neptune, in contrast, were very poorly known until the space era, which, in their case, started with the launch of the second Voyager spacecraft, in 1977. Prior to that date, the available information about these two planets was limited to poor-quality images, which, still, provided evidence for temporal variability and climatic changes in the case of Neptune. Hydrogen and methane were for long the only atmospheric species detected from ground-based spectroscopy.

Our knowledge of the giant planets has been entirely revised with the two sets of NASA spacecraft, Pioneer 10 and 11 and later Voyager 1 and 2. The four spacecraft encountered Jupiter in 1973 (Pioneer 10), 1974 (Pioneer 11) and 1979 (Voyager 1 and 2) respectively; Jupiter was later extensively studied between 1995 and 2000 by the Galileo mission, launched in 1989. Saturn was first encountered by Pioneer 11 in 1979, then by Voyayer 1 and 2 in 1980 and 1981. Voyager 2 continued its journey to encounter Uranus in 1986 and Neptune in 1989, completing the first *in situ* space exploration of the giant planets and their systems. This space program turned out to be an outstanding scientific success. In the future, scientists are looking for the long-term exploration of Saturn by the Cassini mission arriving there in 2004; for Uranus and Neptune, no further space exploration has yet been scheduled.

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In addition to *in situ* space exploration, space observatories in Earth orbit have greatly contributed to our knowledge of the giant planets. The first of them was the International Ultraviolet Observer (IUE), a cooperative project of NASA, ESA and the UK, launched in 1977, which explored the ultraviolet sky for almost twenty years. The next step was the Hubble Space Telescope (HST), a NASA/ESA mission in operation since 1989, which has been providing unprecedented quality images, as well as UV spectra, of all sorts of astronomical sources. The third space observatory to be used for planetology was the Infrared Space Observatory (ISO), an ESA mission with NASA and Japanese participations, in operation between 1995 and 1998, which recorded high sensitivity images and spectra in the infrared range. Two major missions, currently under development, are expected to be the next observatories performing planetary observations: the Far Infra-Red and Submillimeter Telescope (FIRST), an ESA mission with a possible contribution from NASA, will explore the long-wavelength range of the electromagnetic spectrum with unprecedented sensitivity and spectral resolution, and the Next Generation Space Telescope (NGST), developed by NASA with a potential ESA participation, will be a follow-up of the HST with an extension of its spectral range toward the infrared.

THE GIANT PLANETS BEYOND JUPITER

It is possible to understand the general properties of the giant planets (such as their large size, low density and large number of satellites) in the light of their formation scenario. This so-called "nucleation scenario", now widely accepted by the scientific community, is based on a whole set of observational data concerning the dynamics of solar-system bodies and their chemical composition, as well as the analysis of star-forming regions and protoplanetary disks, which bring stringent constraints to theoretical models. Following the initial concepts proposed by Emmanuel Kant and Pierre-Simon de Laplace in the XVIIIth century, the current scenario assumes that the Solar system was formed after the gravitational collapse of a protosolar cloud into a disk, in which solid particles accreted together through collisions to form first planetesimals, and later larger bodies (Cassen and Woolum 1999). The chemical composition of this protosolar cloud, made of interstellar matter, was likely to reflect the cosmic abundances, i.e. include first hydrogen (about 75%), then helium (about 25%), then traces of other heavier elements (O, C, N, …).

In the vicinity of the Sun, where the terrestrial planets formed, the temperature was probably such that only heavy elements (silicates and metals) were in solid form; these elements represent only a small fraction of the cosmic matter. In contrast, at large heliocentric distances, where the giant planets formed, most of the matter, apart from hydrogen and helium, was solid, in form of ices (H_2O, CH_4, NH_3, …). These ices, incorporated into the planetesimals, were abundant enough to form massive cores (about ten to fifteen terrestrial masses, according to theoretical models), which could in turn accrete the surrounding protosolar nebula, mostly made of hydrogen and helium. This simple first-order scenario can account for the large sizes and the low densities of the giant planets, as well as their ring and satellite systems.

According to the nucleation scenario (Mizuno 1980), all giant planets should have formed from an initial core of comparable mass. Comparing this number (10–15 terrestrial masses) to the actual sizes of the giant planets immediately shows a distinction between the four giants. Jupiter and Saturn, whose initial core is 3 to 10% of their total mass, are mostly gaseous, while Uranus and Neptune, with an initial core of more than 50% of their total mass, can be called the icy giants. What can be the origin of this difference? It has been suggested that Uranus and Neptune, located farther from the Sun where the density of the disk was lower, took a longer time than Jupiter and Saturn to accrete their initial cores. In this case, the accretion of the surrounding gas around Uranus and Neptune may have happened after most of the gas was blown away by the strong solar wind expelled by the early Sun in its T-Tauri phase, and Uranus and Neptune would have found much less protosolar gas available for their accretion. This is no more than a possible explanation, however; there are still many open questions about the formation scenarios of the giant planets, and the recent discovery of many "giant" exoplanets in the close vicinity of their star raises new problems, currently unsolved, about their formation.

Apart from the question of their origin, giant planets, as observed today, are far from being fully understood. Among the major issues are their internal structure, the nature of their internal source of heat, the composition of their clouds and their meteorology. The four giant planets were considered for long as being similar to one another; however, recent observations, especially through space exploration, has revealed that the giant planets, like the terrestrial ones, are unique worlds by themselves, and the reasons for these differences remain to be solved. The main orbital and physical parameters of the giant planets are summarized in Table 1; their chemical composition is given in Table 2. In Table 3, abundance ratios in the giant planets are compared to solar and protosolar values.

PLANETS BEYOND NEPTUNE

Early in the XXth century, it was announced by some astronomers, including Percival Lowell, that the orbital motions of Uranus and Neptune could not been explained without the gravitational perturbations of another planetary body, located at further distances from the Sun. This new object called "Planet X" was unsuccessfully searched for during the following decades. As a result of this observing campaign, however, the small Pluto was discovered in 1930 by Clyde Tombaugh. With a diameter of about 2400 km and a density close to $2\,g\,cm^{-2}$, Pluto was not able to account for the orbit anomalies mentioned above. In 1978 however, a satellite, called Charon, was detected around Pluto by James Christy from a study of Pluto's orbital trajectory. Pluto has a distinctly eccentric orbit ($e = 0.246$), that is conspicuously inclined against the ecliptic plane ($i = 17° 10'$).

No bigger planet was found after Pluto, but a whole family of smaller objects, physically similar to Pluto and later called Trans-Neptunian Objects (TNOs) have been discovered during the past decade in the Edgeworth-Kuiper Belt, between 30 and 50 AU (Levison and Weissman 1999). The existence of this belt was predicted independently, on theoretical grounds, by Kenneth Edgeworth and Gerard Kuiper in the 1940–50s. They argued that the expected density of the protoplanetary disk, beyond Neptune, should have been too low to allow the formation of large bodies like the giant planets, but should have been sufficient for the formation of planetesimals, comets and possibly very small planets. It was later suggested by Julio Fernandez that this belt could be the reservoir for short-period comets which have a low inclination. These theoretical studies motivated new observing campaigns which benefited from the use of large ground-based telescopes and high-sensitivity detectors. The first TNO was detected in 1992 by David Jewitt and Jane Luu. As of 1 January, 2000, about 200 objects have been found with diameters larger than 100 km. As in the case of comets, their albedo is expected to be low (a few percent). It now appears that the TNOs are members of a new family of solar-system objects which could be as many as 100 000 (with a diameter above 100 km) in the Edgeworth-Kuiper Belt, with a total mass of a few tenths of a terrestrial mass. The existence of this new class has important implications on physico-chemical and dynamical models of solar-system formation. The search for TNOs and the spectroscopic study of the detected objects have become a new, rapidly exploding field of research.

Most of our knowledge regarding Pluto and the TNOs has come from ground-based astronomy (see Stern and Yelle 1999, for a review). In particular, in the case of Pluto, two methods have been very powerful. The first one is the observation of mutual occultations and transits of Pluto and Charon, in the beginning of the 1980s, which provided a determination of the masses and densities of both objects. The second method is the observation of a stellar occultation by Pluto in 1988, which showed evidence for a stable atmosphere around Pluto. This atmosphere, dominated by nitrogen N_2 with a minor contribution of CH_4, shows remarkable similarities with that of Neptune's satellite Triton. Finally, ground-based infrared spectroscopy has allowed the detection of several ices on Pluto's surface (N_2, CO, CH_4). Water ice, in contrast, was found on Charon, which confirms that Pluto and Charon are different in nature, as illustrated by their different densities. The orbital, physical and chemical properties of Pluto and Charon suggest an origin different from the planetary subnebular material from which the outer satellites formed. It has been suggested that Pluto and Charon accreted independently in the outer solar system and later collided, which led to the binary system observed today (Mueller and McKinnon 1997; Stern and Yelle 1999).

In addition to the ground-based exploration of Pluto, significant information has come from HST images of Pluto's surface which have shown evidence for a differentiation of its surface. The same conclusion came from observations of Pluto's far-infrared flux with ISO. Both HST and ISO have also been used for measuring the visible and far-IR fluxes of a few TNOs. There has been no *in situ* space exploration of Pluto so far, but a flyby mission (Pluto Fast Flyby) is currently under study at NASA.

THE SPACE MISSIONS

The flyby missions: Pioneer 10/11 and Voyager

Following a series of Pioneer spacecraft devoted to the exploration of the Moon and the solar wind, Pioneer 10 and Pioneer 11 were designed by NASA for a low-cost exploratory mission to Jupiter (Lasher 1997). In addition to the exploration of the jovian environment, the major objectives were to study the interplanetary medium beyond the Mars orbit and to investigate the possible hazards in crossing the asteroidal belt. After the success of the Pioneer 10 flyby of Jupiter (4 December 1973), Pioneer 11 was retargeted to allow a Saturn flyby after the Jupiter encounter (3 December 1974). The Saturn flyby took place on 1 September 1979. Among the 11 instruments of the scientific payload were an imaging photopolarimeter, a UV photometer, an IR radiometer, several plasma physics instruments and two impact detectors.

These flybys provided the first short-range images of Jupiter, Saturn and the Saturn rings, showing with unprecedented detail the structure of the jovian belts and zones, the Great Red Spot and Saturn's ring system. Another highlight of these missions was the first measurement of the jovian magnetic field (previously detected from ground-based radio-emission of Jupiter) and the first detection of Saturn's magnetosphere. Pioneer 10 and 11 also demonstrated that spacecraft could survive after crossing the asteroid belt, and thus opened the road to future more sophisticated missions.

Figure 1 The planet Saturn as seen from Voyager 1 on 18 October 1980, from a distance of 34 million km. Colors have been enhanced to better show the contrasts in the belt-zone structure (NASA).

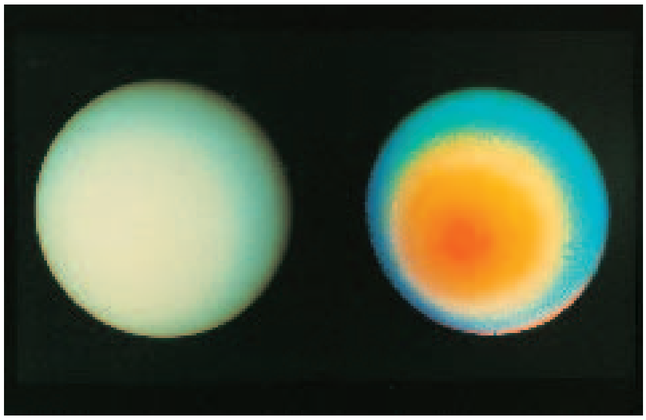

Figure 2 The planet Uranus as seen from Voyager 2, one week prior to the encounter (January 1986), from a distance of 9 million km. Left side: real colors; right side: false colors (NASA).

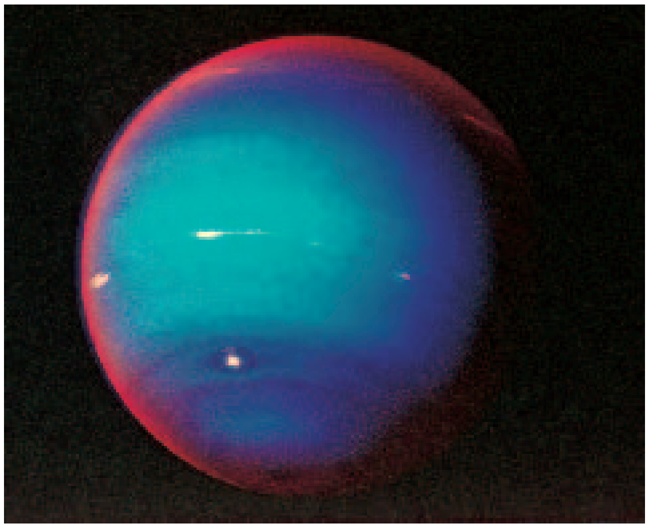

Figure 3 The planet Neptune as seen by Voyager 2 at the time of encounter (August 1989). The image is a false-color combination of 3 exposures in 3 different filters. The deep blue color (which corresponds to the real color) is due to large abundances of gaseous methane. White spots are believed to be high-altitude CH_4 cirrus. The red color, which is not real, corresponds to high-altitude haze in Neptune's stratosphere (NASA).

Following this success, Voyager 1 and 2, two Mariner-type vehicles, were launched by NASA in September 1977 for a flyby exploration of the four giant planets (Miner 1997). Voyager 1 encountered Jupiter on 5 March 1979 and Saturn on 12 November 1980. Voyager 2 encountered Jupiter on 9 July 1979, Saturn on 25 August 1981, Uranus on 24 January 1986 and Neptune on 25 August 1989. The two probes are expected to send data back to Earth until about 2015, where they will be at 130 AU from the Sun. Their objective is to detect the heliopause, defining the limit between the solar-system plasma and the interstellar medium, which is expected to occur, according to the Voyager data, between 110 and 160 AU from the Sun.

The Voyager spacecraft included in their scientific payload (11 instruments) a camera, IR and UV spectrometers, a magnetometer, and charged-particles, plasma and radio wave experiments. The camera observed the cloud structure and the dynamical phenomena of the atmospheres (Figures 1 to 3), whose temperature structure and chemical composition were inferred from the IR spectrometer IRIS; the UV spectrometer probed the stratospheres and the ionospheres.

A huge amount of new results and discoveries came out of the Voyager exploration of the giant planets. Among the highlights are the first detection of active volcanism on Io, the detection of Jupiter's rings and the fine structure of the other planetary rings, the composition and structure of Titan's and Triton's atmospheres, the first observation of Uranus and Neptune's magnetospheres, the first observation of the surfaces of Miranda and Triton, and the detection of many new small satellites around the four giant planets.

The space observatories: IUE, HST and ISO

The IUE satellite consisted of a 45-cm telescope equipped with two spectrographs, giving a resolving power as high as 10^4 over the 1150–3200 Å spectral range (Boggess and Wilson 1987). UV spectra of the giant planets recorded by IUE have allowed to probe their upper atmospheres, and in particular their aeronomy and photochemistry. Above about 1600 Å, the UV radiation comes from the

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