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The outer solar system

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Abstract. The outer solar system extends beyond a heliocentric distance of 5 AU. It contains the giant planets and their systems (rings and satellites), the Kuiper belt, the comets (except those which approach episodically the inner solar system) and, at its outer edge, the Oort cloud. The outer solar system physically corresponds to the region located outside the « snow line » which corresponded to the distance of ice condensation in the protodolar disk, and thus made the frontier between the terrestrial and the giant planets at the time of the planets' formation. The outer solar system is charaterized by a very large variety of objects, even within a given class of objects. Each of the giant planet has its own properties, as well as each of the outer satellites and the ring systems ; all are the products of specific conditions which determined their formation and evolution processes. The existence of the Kuiper belt, suspected on theoretical bases since the 1940s, has been confirmed since 1992 with the observation of over 1200 trans-neptunian objects. Thanks to the the developments of more and more performing ground-based instrumentation and the use of large telescopes, these objects are now studies in a statistical way, both dynamically and physically, and these studies are precious for constraining the early formation models of the solar system.

1 Introduction

A simple look at the orbital and physical characteristics of the eight solar-system planets shows that all these objects fall in two main categories (Table 1). At low heliocentric distance ($Rh < 2$ AU), the terrestrial planets (Mercury, Venus, the Earth and Mars) have relatively small sizes, low densities, and a small number of satellites ; their atmosphere (apart from Mercury which has none) is only a negligible fraction of their total mass. In contrast, at $Rh > 5$ AU, the giant planets (Jupiter, Saturn, Uranus and Neptune) have larges masses, low densities, a ring system and a large number of satellites ; their atmosphere is, in all cases, a significant fraction of their total mass. Beyond Neptune, Pluto is a small icy object, located on a very elliptical and highly inclinated orbit. Since the 1990s, we know that Pluto is one of the biggest representatives of a new population of outer solar-system objects, called the trans-neptunian objects and located in the Kuiper belt. Since 2006, the IAU has recognized this status by removing Pluto from the official list of solar-system "planets".

The planets' main properties allow us to set the limits of what we will call "the outer solar system". In what follows, we will see that the main classification in terrestrial and giant planets is a direct consequence of the formation scenario of the solar system. We will then review the different classes of outer solar-system objects : giant planets, rings and satellites, comets and Kuiper-Belt objects, with special emphasis on the atmospheres of planets, outer satellites and comets.

2 The formation of the solar system

The formation model of the Sun and the solar system, called the model of the primordial nebula, was first suggested by Kant and Laplace in the XVIIth and XVIIIth centuries, and is

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Table 1. Orbital and physical properties of solar-system planets.

Name	Semi-major axis (AU)	Eccentricity	Inclination to ecliptic (°)	Sidereal period (yr)	Equatorial diameter (D_E)	Mass (M_E)	Density (g/cm^3)	Polar inclination vs. Orbital plane (°)
Mercury	0.3871	0.2056	7.0048	0.2408	0.382	0.055	5.44	0
Venus	0.7233	0.0068	3.3995	0.6152	0.949	0.815	5.25	2.1
Earth	1.0000	0.0167	0.0000	1.0000	1.000	1.000	5.52	23.5
Mars	1.5237	0.0934	1.8506	1.8807	0.533	0.107	3.94	24.0
Jupiter	5.2034	0.0484	1.3053	11.856	11.19	317.8	1.24	3.0
Saturn	9.5371	0.0541	2.4845	29.424	9.41	95.1	0.63	26.7
Uranus	19.1913	0.0472	0.7699	83.747	3.98	14.6	1.21	98
Neptune	30.0690	0.0086	1.7692	163.723	3.81	17.2	1.67	29

now widely accepted in the scientific community. Its basic justification lays on the fact that planetary orbits are all quasi-coplanar (i.e. close to the ecliptic plane, defined by the Earth orbit) ; they are all circular and concentric, and they all rotate counter-clockwise, as does the Sun (as seen from the north ecliptic pole). This strongly suggests that the Sun and planets formed within a disk, following the gravitational collapse of a rotating nebula. Observations performed over the past decades, especially with the HST and with ground-based millimeter interferometers, have shown that such a phenomenon is currently observed on nearby young stars, surrounded by protoplanetary disks.

After the collapse of the disk, matter contracts at the center to form the proto-Sun. Within the disk (made of gas and dust, as does interstellar matter with cosmic abundances, and probably mostly turbulent), following local instabilities, small particles start to aggregate and grow through multiple collisions to build planetesimals. In turn, these planetesimals form bigger objects which accrete the surrounding matter by gravity. Using numerical computations and statistical methods, it is possible to simulate numerically the evolution of a large number of particles over the age over millions of years. Results show that, in the region of terrestrial planets ($Rh < 2$ AU) the accretion process leads to the formation of a small number of Earth-size planets. It is also possible to simulate the formation scenario of the giant planets and the Kuiper-Belt objects.

In the light of this scenario, it is possible to find a natural explanation to the two classes of planets, terrestrial and giant. The key parameter is the nature and amount of the solid matter available at a given heliocentric distance to be incorporated into a planetary body. We have seen that the protosolar disk is made of interstellar matter, i.e. mostly hydrogen and helium. All the other elements account to less that 2 percent of the total mass and, following the cosmic abundances, the lighter elements (O, C, N) are the most abundant, while the heavier ones (silicates, metals) are less abundant (Table 2).

Within the protosolar disk, the temperature decreases as the heliocentric distance increases, and also decreases generally everywhere as a function of time. Near the Sun ($Rh < 2$ AU), the temperature was likely to be over a few hundred K at the time of planets' formation. The only matter available in the solid form was metals and silicates, i.e., as mentioned above, a small fraction of the total mass. Thus, the few objects formed in this region were small and rocky planets.

In contrast, at larger heliocentric distances ($Rh > 5$UA), the temperature must have been low enough for oxygen, carbon and nitrogen (combined in H_2O, CH_4, $NH_3, \ldots$) to be in icy form. Since they are more abundant than heavier elements, big icy cores (as big as 10 terrestrial masses) could be built. At that stage, models predict that their gravity field is sufficient to accrete the surrounding matter, mostly made of hydrogen and helium. This process leads to the formation of large planets with low densities ; the collapse phase leads to the formation of a mini-disk, in the equatorial plane of each giant planet, where rings and regular satellites are formed.

Table 2. Chemical composition of giant planet atmospheres.

Species	Jupiter	Saturn	Uranus	Neptune
H_2	1	1	1	1
HD	4 (-5)	4 (-5)	1.1 (-4)	1.3 (-4)
He	0.157	0.10-0.16	0.18	0.23
CH_4 (trop) CH_4 (strat)	2.1 (-3) $\ll$	4.4 (-3) $\ll$	2 (-2) 7 (-5)	4 (-2) 7 (-4)
$^{13}CH_4$	2 (-5)	4 (-5)		
CH_3D (trop)	2.5 (-7)	3.2 (-7)	1 (-5)	2 (-5)
C_2H_2	1 (-7) @ 1 mbar	2 (-7) @ 1 mbar	3 (-7) @ 0.2 mbar	1 (-7) @ 1 mbar
$^{12}C^{13}CH_2$	*			
C_2H_6 (strat)	1 (-5) @ 1 mbar	4 (-6) @ 1 mbar		1.3 (-6) @ 1 mbar
CH_3C_2H (strat)	*	6 (-10) @ 1 mbar		
C_4H_2(strat)		9 (-11) @ 1 mbar		
C_2H_4 (strat)	7 (-9) @ 1 mbar	*		*
C_3H_8 (strat)	6 (-7) @ 1 mbar			
C_6H_6 (strat)	2 (-9) @ 1 mbar	*		
CH_3(strat)		7 (-8) @ 0.3 μbar		5 (-8) @ 0.2 μbar
NH_3 (trop)	2 (-4) @ 3 bar	3 (-4) @ 3 bar		
$^{15}NH_3$ (trop)	4 (-7)			
PH_3 (trop)	6 (-7)	2 (-6)		
GeH_4 (trop)	7 (-10)	2 (-9)		
AsH_3 (trop)	3 (-10)	2 (-9)		
CO (trop) CO (strat)	1.5 (-9) 1.5 (-9)	2 (-9) 2 (-9)	3 (-8)	1 (-6)
CO_2 (strat)	3 (-10) @ 1 mbar	3 (-10) @ 1 mbar		5 (-10) @ 1 mbar
H_2O (trop)	1.4 (-5) @ 3 bar	2 (-7) @ 3 bar		
H_2O (strat)	1.5 (-9) @ 1 mbar	0.2-2(-8) @ 1 mbar	7(-10) @ 0.1 mbar	2(-9) @ 0.1 mbar
HCN				3 (-10)
H_3^+	*	*	*	

More precisely, the nature of the giant planet (i.e. the relative fraction of its icy core, as compared to its total mass) is a function of the amount of matter available at the time of the gravitational collapse following the core formation. Both Jupiter and Saturn are very massive (318 and 95 terrestrial masses respectively), which means that they are mostly composed of the protosolar gas: they are called the gaseous giants. In contrast, Uranus and Neptune (called the icy giants) have total masses of 14 and 17 terrestrial masses respectively, which means that more than half of their total mass is made of their icy core. What can be the cause for such a drastic difference ? A possible explanation is that in the case of the icy giants, formed at larger heliocentric distances, more time was needed for their icy core to reach the critical size leading to gravitational collapse. This phase might have happened after most of the gas in the disk had dissipated, following an intense activity phase ("T Tauri phase") of the early Sun.

The "snow line", where ice condensation begins, marks the limit between the terrestrial and the giant planets. Actually, water condensation is mostly responsible for this limit, for two reasons: first, water is the most abundant ice, in view of the relative abundance of oxygen with respect to the other heavy elements ; second, water is by far the first molecule to condense as the temperature slows down (Fig. 1). Water condensation typically takes place at temperatures of about 180 K. At the time of the planet formation, the snow line is believed to have been located at 4–5 AU. Now, this limit is rather at about 2–3 AU ; this is the distance where the onset of cometary activity (mostly driven by water) takes place.

The giant planets' formation scenario described above, called the nucleation scenario, was first suggested by Mizuno [3] and later developed by Pollack et al. [4]. It is not the only possible one, however. For several decades it was suggested that giant planets formed directly from gravitational collapse within the disk, as the consequence of a local instability, and this scenario might apply in the case of some extrasolar giant planets. In the case of the solar-system giant

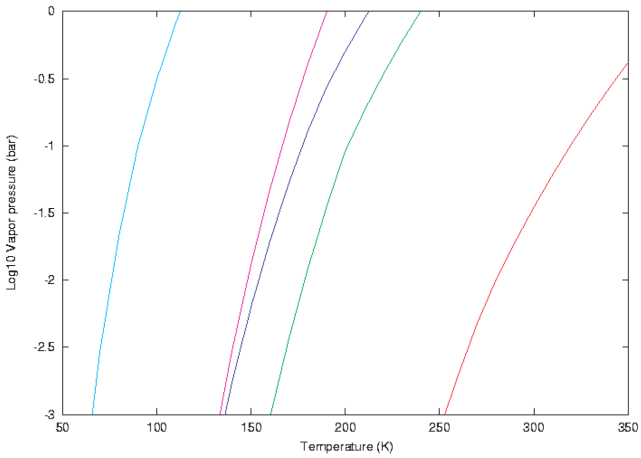

Fig. 1. The saturation curves of various ices. From right to left: H_2O, NH_3, H_2S, CO_2, CH_4. Saturation laws are taken from Atreya [1]. The figure is taken from Encrenaz [2].

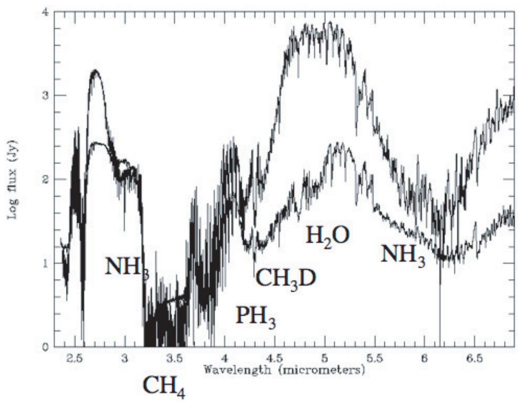

Fig. 2. The infrared spectrum of Jupiter and Saturn observed by the Short Wavelength Spectrometer (SWS) aboard the Infrared Space Observatory (ISO). The higher curve is Jupiter at all wavelengths except at $3.0\,\mu$m where Saturn's flux is higher. The $5-\mu$m spectral region is a window where the thermal flux comes from the lower troposphere. The figure is taken from Encrenaz [6].

planets, there is a strong argument in favor of the nucleation model, based on the elemental and isotopic abundance ratios measured in these planets. This will be discussed in more detail below.

3 The atmospheres of the giant planets

3.1 Atmospheric composition

We have seen that giant planets are mostly composed of hydrogen and helium, with the minor constituents accounting for less than a percent (or 2 percent in the case of Uranus and Neptune). Methane (CH_4) is the most abundant of the minor constituents. Minor atmospheric constituents (Table 2) fall in three distinct categories: (1) the tropospheric species, coming from the bulk composition of the planets (Fig. 2); (2) the hydrocarbons, coming from the dissociation of methane in the stratosphere; (3) the oxygen species which come from an incoming flux of oxygenized material. The origin of this flux could be either local (rings or satellites) or interplanetary (micrometeoritic or cometary flux). As an example, the collision of comet

Table 3. Enrichments in heavy elements in the giant planets (after Owen and Encrenaz [8]).

Planet	Mass (M_E)	Observed enrichment in heavy elements	Mass of Initial core required to fit the observed enrichment	Origin of measurements
Jupiter	318	4.0+/−2.0	12 (+10, −6)	CH_4/H_2 (thermal emission) GCMS (C, N, S, Ar, Kr, Xe)
Saturn	95	9.0+/−1.5	11 +/− 2	CH_4/H_2 (thermal emission)
Uranus	14	40 (+15, −10)	8.5 (+2.5,−2.0)	CH_4/H_2 (reflected sunlight)
Neptune	17	55+/−15	13 +/− 3	CH_4/H_2 (reflected sunlight)

Note: This table illustrates that the enrichment in heavy elements measured in the giant planets can, for all giant planets, be explained by a simple model assuming an initial icy core of about 12 M_E, surrounded by an envelope of protosolar matter with cosmic abundances. All ices are assumed to be equally trapped in the ices, and the interior of the planet is assumed to have been warm enough for its composition to be re-homogeneized after the collapse of the protosolar envelope.

Shoemaker-Levy 9 with Jupiter, in 1994 (see Section 5.3.1), led to the formation of H_2O, CO, OCS and other species, all resulting from shock chemistry.

Most of our knowledge about the chemical composition of giant planets comes from remote sensing infrared spectroscopy, obtained from ground-based telescopes or the european Space Infrared Observatory (ISO) which operated in Earth orbit in 1995–1998. The element (in particular C/H) and istope (in particular D/H) abundances have brought a precious diagnostic in support of the nucleation model of the giant planets. Indeed, if we assume that all giant planets started with an initial icy nucleus of about 12 terrestrial masses, followed by the accretion of the surrounding protosolar gas (mostly made of hydrogen and helium), and if we assume that the matter was rehomogeneized after the heating phase following the collapse of the gas, then we expect an enrichment of heavy elements ("heavy" meaning an atomic mass of 12 or higher) with respect to hydrogen, as compared with the solar abundances. Considering the present masses of the giant planets (318, 95, 14 and 17 terrestrial masses from Jupiter to Neptune respectively), one can infer that the expected enrichment in heavy elements is 4, 9, 30 and 45 from Jupiter to Neptune respectively. It is striking to observe that this enrichment is indeed observed on the four giant planets (Table 3). In the case of Jupiter we have several measurements coming from the Galileo probe which entered Jupiter's atmosphere in December 1995 (Owen et al. [5], Fig. 3). In the case of the other giant planets we only have C/H, inferred from CH_4 remote sensing spectroscopy measurements.

Another diagnostic is provided from the D/H measurement in the giant planets, inferred from the HD/H_2 and the CH_3D/CH_4 measurements. The D/H ratio is known to be enriched in ices, as a result of ion-molecule and molecule-molecule reactions at low temperatures. A high D/H ratio is thus a diagnostic of a low temperature formation. Because Uranus and Neptune are mostly made of their initial icy cores, one expects their D/H ratio to be enriched with respect to one of Jupiter and Saturn, which should be close to the protosolar one. This is indeed what has been observed with the ISO satellite, in agreement with ground-based measurements in the near-infrared range.

3.2 Temperature and cloud structure

All giant planets are characterized by a tropospheric region, where the convection dominates with a thermal gradient close to the adiabatic value, which extends from deep levels (serveral tens and hundreds of bars) up to the tropopause, at about 0.1 bar (Fig. 4). The tropopause is the region where the temperature is minimum: about 110 K for Jupiter, 95 K for Saturn, and 52 K for Uranus and Neptune. The stratosphere, above this level, is characterized by an increase of temperature with altitude. This increase is due to the absorption of the solar flux by aerosols and by hydrocarbons produced by the methane photodissociation. At higher altitudes,

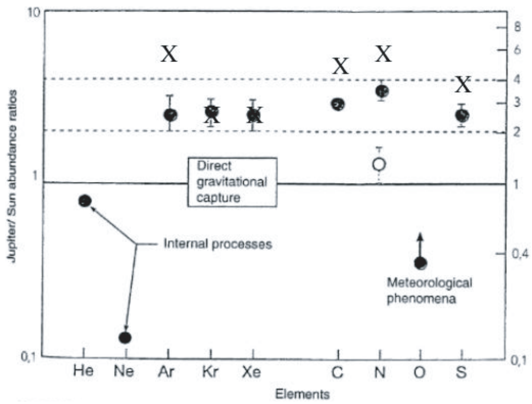

Fig. 3. The enrichment in heavy elements in Jupiter relative to the solar (cosmic) values, as measured by the GCMS aboard the Galileo probe. In ordinate, the 1 value corresponds to the solar value (no enrichment). Six elements are found to be enriched by a factor initially estimated to 3+/− 1 (black circles). Following the revision of the solar abundances by Grevesse et al. [7], these values have been reestimated to 4+/− 2 (crosses). Three elements appear to be depleted with respect to the solar value: He and Ne (probable condensation in Jupiter's interior within the hydrogen metallic ocean) and O (probable depletion of H_2O due to convective circulation in Jupiter's troposphere). The figure is adapted from Owen et al. [5].

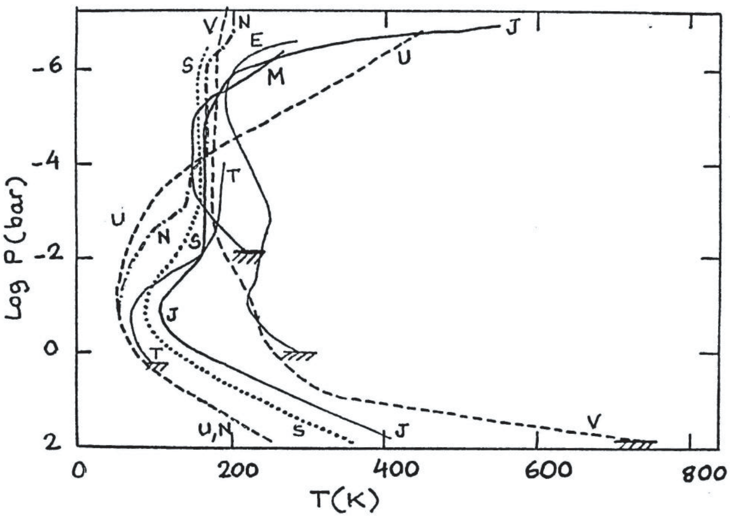

Fig. 4. The thermal structure of planetary atmospheres. J = Jupiter, S = Saturn, U = Uranus, N = Neptune, T = Titan, E = Earth, M = Mars, V = Venus. The atmospheres of the four giant planets are characterized by a convective region (the troposphere) where the temperature decreases as the altitude increases. The tropopause, which corresponds to a minimum of temperature, appears at 0.1 bar for all giant planets. Above this level, in the stratosphere, the temperature increases again with the altitude.

the temperature heating is due to either planetary waves or high-energy particles or both, and varies from a planet to another.

The thermal structures of the giant planet atmospheres induce a cloud structure which can be predicted from thermochemical models, on the basis of a given chemical composition. In the case of Jupiter and Saturn, a NH_3 cloud is expected at about 0.5–1 bar. At lower levels, clouds of NH_4SH and H_2O are expected at pressure levels of a few bars. In the case of Uranus and Neptune, which are much colder, most of the species are expected to condense at observable levels (i.e. above the 1-bar level). Hydrocarbon hazes, including C_2H_6, are expected in the

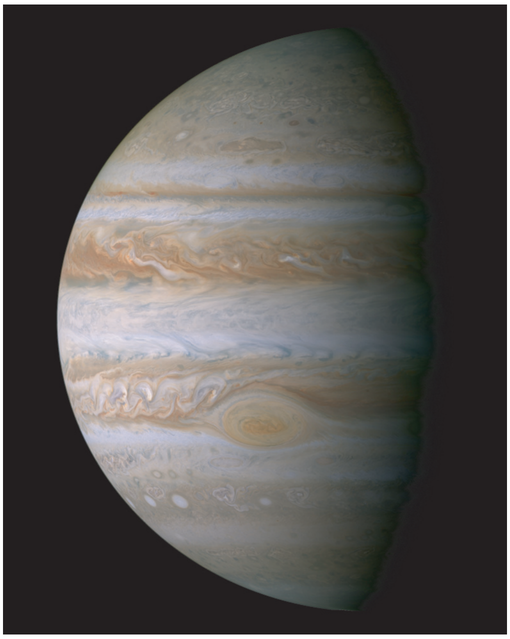

Fig. 5. The planet Jupiter, observed by the camera of the Cassini spacecraft during its flyby of the planet in December 2000 (© NASA).

stratosphere. CH_4 is expected to condense at about 1 bar, while a H_2S cloud could be present below, at a few bar level. H_2O is expected to condense at a pressure level of a few tens of bars.

3.3 Atmospheric circulation

In the case of the terrestrial planets, the atmospheric circulation is mostly driven by the seasonal variations of the incoming solar flux. This induces, for Venus, the Earth and Mars, a "Hadley-type" circulation, characterized by the presence of convective cells. In the case of the giant planets, the Hadley circulation also exists, with a larger number of cells (which create the well-known belt-and-zone system of Jupiter and Saturn), due to their higher rotation period (Fig. 5 and 6). Also, the presence of an internal source of energy (except in the case of Uranus) is an additional parameter to the overall atmospheric circulation. Several small-scale phenomena also occur: Great Red Spot on Jupiter, white ovals on Jupiter and Saturn, Dark Spot on Neptune, which seem to be of anticyclonic origin.

3.4 Dynamical history of the giant planets

Over the past decades, the development of high-power computers has led to a new science, the numerical simulation of the early dynamical histories of solar-system objects. It is now possible to simulate the birth and growth of the planetesimals which later became the solar-system planets. These calculations have brought important conclusions regarding the history of the outer planets. Like many exoplanets, the solar-system giant planets seem to have encountered some migration effect during their history, but this migration must have been much more moderate as the one observed in the case of many exoplanets. Jupiter would have moved slightly inward (possibly from 6 to 5 AU) while the three other giant planets would have moved outward (with Saturn starting from about 8 AU and both Uranus and Neptune from about 15 AU). In such a configuration, at a given time (about 800 My after the giant planets' formation), the Jupiter-Saturn system must have crossed the 2:1 resonance (this is the geometrical configuration for which Saturn's rotation period is twice the one of Jupiter). The effect must have been very strong on the eccentricities and inclinations of all solar-system small bodies, including asteroid

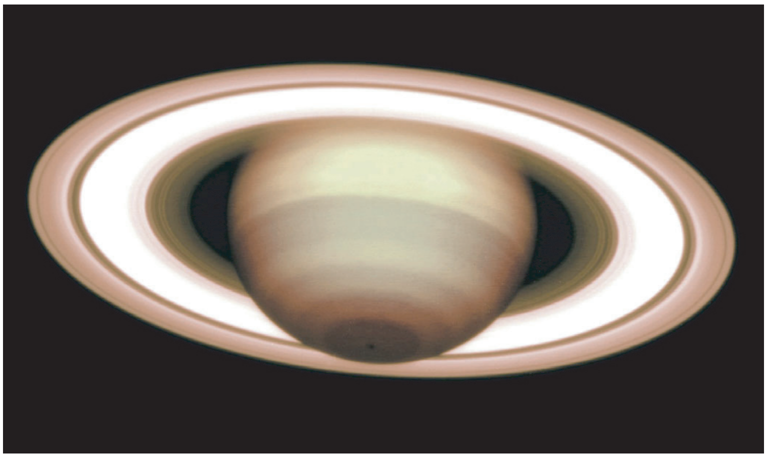

Fig. 6. Planet Saturn as observed with the NAOS-CONICA (NACO) instrument at the Very Large Telescope (VLT) of the European Southern Observatory at Cerro Paranal, Chile (©ESO).

families, trojans and trans-neptunian objects. Another strong effect would have been the Late Heavy Bombardment (LHB) which left traces on the surfaces of all bare solar-system bodies. All these effects are now observed today on the orbits and surfaces of the small bodies, and do confirm the scenario described above.

3.5 Open questions and future plans

Today it can be said that the formation scenario of the giant planets is currently well understood. However, many questions remain unsolved and will require further investigations, from observational, theoretical and experimental points of view.

A first question is related to the temperature at which Jupiter's planetesimals were formed. Indeed, the data obtained from the Galileo probe suggest that many heavy elements (including the rare gases Ar, Kr and Xe) do show the enrichment factor of 4 mentioned above. The same is true for nitrogen and sulfur. This constant enrichment factor raises a problem, however. It suggests that all heavy elements were equally trapped in ices. But laboratory measurements seem to show that Ar and N cannot be trapped on ices unless the temperature is lower than 40 K, or even possibly 30 K. At Jupiter's orbit (or even at 6 AU, the possible initial heliocentric distance of Jupiter), the equilibrium temperature should be much higher, above 100 K. So, if Jupiter was formed with low-temperature planetesimals, where did they come from? It is unlikely that Jupiter formed at 30 K and migrated later inward, as the density of matter at such large distances from the Sun would have been too low. The question is thus open presently. We do not know whether the other giant planets show the same behavior or not, because these planets were not visited by in-situ probes and we do not have yet the equivalent of the Galileo mass spectrometer data for them. An urgent objective for future space missions toward the outer solar system would be to send in-situ probes into the interiors of Saturn, Uranus and Neptune in order to determine their elemental composition.

The atmospheric circulation of the giant planets brings another puzzle. Jupiter, Saturn and Neptune are all very active dynamically, which is also probably connected with the presence of an internal source of energy. Uranus, which does not show such an internal source, also has a very low dynamical activity. It is surprising to see how Uranus and Neptune are so different, while they show comparable physical parameters (size, density), and were presumably formed at comparable heliocentric distances. Neptune's stratosphere is warmer and much richer in hydrocarbon and oxygen compounds. The origin of these differences remains to be understood. Ground-based and earth-orbiting observations in the infrared and submillimeter range should be pursued, in particular with the european space mission Herschel, the ALMA network and the future ELT.

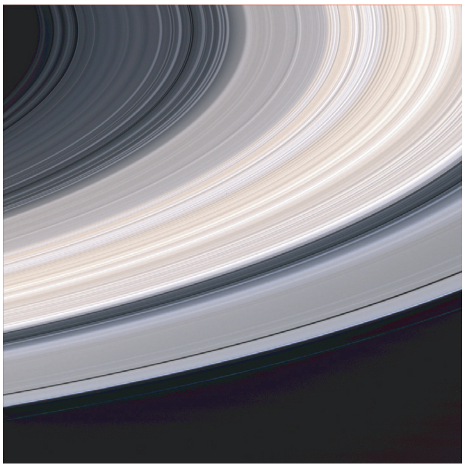

Fig. 7. The rings of Saturn, as observed by the camera of the Cassini orbiter (©NASA).

4 Rings and satellites

The presence of ring systems and numerous satellites around the giant planets is a natural consequence of the formation scenario. Indeed, in the collapse phase which follows the building up of their initial icy cores, the surrounding protosolar matter falls within a disk which coincides with the equatorial plane of the planets. Ring systems and regular satellites form within these disks. The outer planet systems thus show some analogies with the solar system itself. There are some important differences, however. First, the ratios of the sizes of the outer satellites to their distance to the planet are much larger than the ratios of the planets' diameters to their heliocentric distance. Second, all outer satellites and ring particles are mostly composed of ice, and mostly of water ice ; this results from the low temperature of the environment where they formed.

4.1 Ring systems

Ring systems are found in the immediate vicinity of the giant planets, within a few planetary radii. They come from the disruption of small satellites within the Roche limit. This limit defines the minimum planetary distance beyond which a satellite is not destroyed by the differential forces induced by the tidal forces generated by the gravity field of the planet. If the density of the satellite is the same as the planet's one, this limit is about 2.5 planetary radii. Ring systems of the outer planets show an incredible diversity, with Saturn's system being known since several centuries and the three other ones discovered only a few decades ago.

4.1.1 Saturn's rings

Saturn's ring system was observed by Galileo in 1610, and properly interpreted by Huygens in 1654. In 1675, Cassini discovered, between the two main rings A and B, the division which since that time carried his name. The inner C ring was found in 1850. At the end of the XVIIIth century, Laplace already showed that the rings could not be solid, as they would not be stable against tidal forces, and Maxell later suggested that the rings were made of individual grains with different rotation periods, in accordance with Kepler's third law. The study of Saturn's rings has been completely changed by space exploration, with the Voyager encounters in 1980 and 1981, then the Cassini exploration since 2004 (Fig. 7). There are presently 7 ring systems, ranging from the inner D ring at 1.95 saturnian radii up to the outer E ring at 3.95 saturnian radii. This ring, far outside the Roche limit, is associated with the orbit of Enceladus and is believed to be fed by the outgassing of this satellite.

The size distribution of the ring particles ranges over several orders of magnitude, from the micrometer to the kilometer size. In comparison, the overall depth of the ring is extremely small, of the order of a kilometer. This depth is not constant and the rings are actually tilted. Continuous observations by the Cassini orbiter have shown that the ring particles are in permanent mutual interaction and dynamical evolution over very short time scales.

The chemical composition of Saturn's rings has been first studied from ground-based near infrared spectroscopy which has revealed the presence of water ice as the major constituent. More complete studies have been performed by the Cassini orbiter and has shown the presence of traces of other constituents, including oxides.

4.1.2 The ring systems of Uranus and Neptune

As compared with the Saturn system, the rings of Uranus and Neptune are extremely tenuous. They were discovered in 1977 and 1984 respectively, from the ground-based observations of stellar occultation.

In the case of Uranus, nine narrow rings were observed at a distance of Uranus ranging between 1.65 and 2.05 planetary radii. Eight of them have a width lower than 10 km and the last one is less than 100 km in width. The images of Voyager 2, in 1986, confirmed this result and found two small satellites which confine the principal ring. The albedo of Uranus rings is very low, which might be due to the presence of a cover, over water ice, of organic polymers resulting from the irradiation of ices by cosmic rays and/or magnetospheric high-energy particles.

The observation of Neptune's rings in 1984 did not show a complete ring structure but suggested the presence of arcs. In 1989, Voyager 2 observations did show that the rings are complete, but they are thicker at some locations which allowed then to be detected from the gound. This localized increase of matter along the orbit is explained by a resonance effect involving nearby satellites.Voyager has detected two main narrow rings and three others, fainter and wider. Neptune's rings are dark and probably have the same chemical composition as the ones of Uranus.

4.1.3 Jupiter rings

Jupiter's rings, discovered in 1979 at the time of the Voyager 1 flyby, are of very different nature. They are very tenuous, at 1.74 jovian radii, made of small particles, and probably fed through meteoritic bombardment of the nearby satellites or particles trapped in Jupiter's magnetic field.

4.2 The outer satellites

There are two kinds of outer satellites. The first ones are the regular ones, close to the equatorial plane of their planet, with low inclinations and eccentricities ; they were formed after the collapse of the sub-nebula when the giant planets were formed. The others are the irregular ones, characterized by random inclinations and large eccentricities ; they were outer asteroids captured by the gravity field of their planet.

Most of the outer satellites have no stable atmosphere. There are still a few famous exceptions: Titan, Saturn's largest satellite which has a nitrogen-rich atmosphere with a surface pressure comparable to that of the Earth ; Triton, Neptune's satellite which, like Pluto, has also a nitrogen-rich atmosphere with a surface pressure of a few tens of microbars ; Io, Jupiter's closest galilean satellite which has a SO_2-atmosphere of a few nanobars surface pressure. We first consider the outer satellites which have no atmosphere.

As in the case of the ring systems, the variety of physical properties is extreme within the outer satellites. Each of them is a world in itself, as a product of specific formation and evolution processes. This wide range of physical properties can be seen as an indicator of what we can expect to find around extraoslar giant planets...

4.2.1 The outer satellites with no stable atmosphere

4.2.1.1 The galilean satellites

In this category, the most famous bare satellites are the Galilean satellites, discovered by Galileo in 1610. Their distance to Jupiter ranges from 6 to 26 jovian radii, and this variation in the distance to the planet induces considerable differences in their internal and surface properties. Io, the closest one of Jupiter, is subject to very strong tidal forces which affect both its internal structure and its surface where active volcanism takes place presently. Io is the only known solar-system object outside the Earth which shows this behaviour. The volcanism, first detected by Voyager in 1979 and later monitored by Galileo, Cassini and the HST, shows time variations and induces a transient, patchy atmosphere of sulfur dioxide. Because of the low surface temperature (about 110 K), SO_2, mostly outgassed near the equator, tends to condense at higher latitudes. Another pecularity of Io is the torus surrounding its orbit, populated with atoms and ions, mostly sulfur and oxygen, produced by Io's volcanism, which have been observed in the UV.

Europa, the next galilean satellite, is another intriguing body for astronomers. Like the two other galileans, Ganymede and Callisto, its surface is made of water ice. Its interior is believed to be made of water, surrounding a silicate core. Europa, however, is like Io subject to tidal forces, and the corresponding internal energy is sufficient to warm the internal temperature enough for the internal water to be liquid down to the level of the silicate boudary. This potential property makes Europa an exciting target for future astrobiology studies. The question however is: how deep is the icy crust ? According to thermodynamical models, its depth could reach several tens of kilometers. In spite of the potential challenges raised for probing below the surface, Europa is a favored target for future planetary exploration, both for ESA and NASA.

Ganymede and Callisto are the biggest galilean satellites, and, together with Titan, the biggest outer satellites. Their surface is made of a mixture of water ice and rocks. Callisto, far enough from Jupiter to avoid any tidal interaction, is presently inactive. Its surface, heavily covered with craters, is very old. An interesting result about Ganymede was the discovery of an intrinsic magnetic field by the magnetometer of the Galileo orbiter ; it is the only galilean satellite showing that property which might imply the presence of molten iron in its central core.

In addition to the galilean satellites, Jupiter has presently over forty known satellites and the list increases every year. The smallest ones have a size of a few kilometers only.

4.2.1.2 Other bare satellites

The size distribution of Saturn's satellites is very different from the one of Jupiter. The biggest one, Titan, is located at 20 saturnian radii, and all the others are significantly smaller. They are all covered with water ice and probably contain a rocky core in their interiors. One of them, Enceladus, deserves specific attention. The measurements of the Cassini orbiter have shown that outgassing is taking place at the south pole of the satellite, and water has been identified in the plumes. The origin of this mechanism is not fully understood, as Enceladus is too small to generate internal energy and the tidal effects do not seem to be sufficient to induce such effect. Enceladus is thus a puzzle for planetologists, and may be a target for future space exploration. There are over 30 satellites of Saturn presently known.

With the Uranus system, we are back in a size distribution comparable to the galilean system, with five big satellites between 5 and 23 uranian radii. All are dark, which suggests that their surface has been irradiated by cosmic rays or high energy particles coming from Uranus magnetosphere. Miranda, the satellite closest to Uranus, is also the most intriguing. In spite of its small size, its surface exhibits many signs of intense past tectonic activity (faults, valleys. . .). It has been suggested that Miranda might have been disrupted after a collision and later recombined from the debris left in Uranus' orbit. The Uranus system presently includes over 20 satellites.

The system of Neptune is characterized by the presence of Triton, the biggest object. Unlike all other big outer satellites, it is irregular and probably results from a capture. As an effect of this capture, the previous system of regular satellites must have been strongly perturbed,

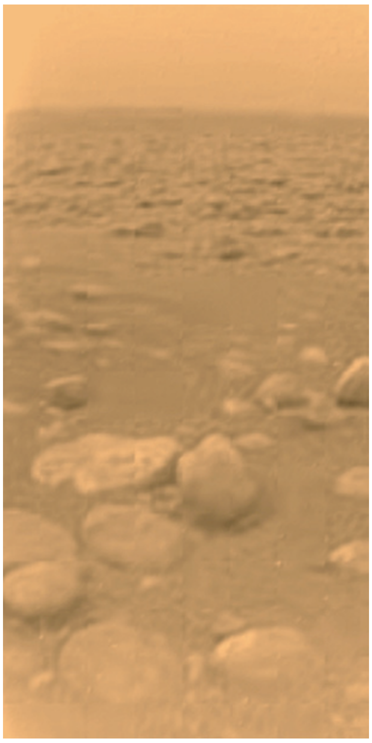

Fig. 8. The surface of Titan as revealed by the Huygens probe as it landed on Titan on January 14, 2005 (©ESA).

with some of them being ejected. Triton has a tenuous stable atmosphere (see below). There are presently over a dozen of known satellites around Neptune.

4.2.2 Titan

Titan, Saturn's biggest satellite, is an exception in itself in the solar system. It is covered by a thick atmosphere of nitrogen, with a surface pressure close to the terrestrial one (1.5 bar). In addition, Titan's atmosphere contains about 2 percent of methane which are photodissociated in the stratosphere, as in the giant planets. Nitrogen destruction by high-energy particles and solar UV photons also leads to the production of nitriles. Titan's atmosphere thus contains a large number of hydrocarbons and nitriles, which are known to be, from laboratory simulation experiments, the building blocks of prebiotic chemistry. For these reasons, Titan is considered as a unique object for astrobiology.

Titan has long been a puzzle for astronomers. First discovered by Huygens in the XVIIth century, the satellite was identified as surrounded by an atmosphere by Comas Sola in 1908, and atmospheric methane was later discovered by Kuiper, in 1944, from near-infrared spectroscopy. There was a long controversy about the surface pressure of Titan in the following decades, with estimates ranging from 2 to 20 bars. The answer was given by Titans' flyby by the Voyager spacecraft in 1980. The surface pressure is 1.5 bars, the surface temperature is 93 K and the atmosphere is mostly composed of nitrogen with 2 percent methane and traces of other gases. The minor components presently identified are H_2, possibly Ar, CO, CO_2, H_2O, hydrocarbons and nitriles.

The Cassini mission, led by NASA and ESA and launched in October 1997, encountered the Saturn system in 2004. The European probe Huygens successfully landed on Titan's surface on January 14, 2005, and transmitted to Earth the first images of the satellite's surface (Fig. 8). The observed lanscape was plain, covered with a deposit presumably made of hydrocarbons, with scattered eroded boulders, probably made of water ice. Later, Cassini's radar discovered the presence of hydrocarbon lakes at northern latitudes, a region which is presently colder than the rest of the satellite as expected by the seasonal cycle.

Titan's thermal profile is, like the giant planets, characterized by a convective region with an adiabatic lapse rate, extending up to the tropopause at an altitude of about 40 km and a pressure level of about 0.1 bar. Above this level, the stratosphere is heated by the absorption of solar flux, which leads to the photodissociation of methane. At higher levels, the destruction of nitrogen leads to the formation of nitriles. As in the case of the giant planets, Titan's upper atmosphere receives an incoming flux of oxygenized components (H_2O, CO_2, possible CO) probably coming from Saturn's rings or satellites, or from an interplanetary flux of micrometeorits and comets. The main surprise, regarding the Cassini's atmospheric results, has come from the Ion Mass Spectrometer instrument, which has discovered hundreds of complex hydrocarbon and nitrile ions in Titan's ionosphere. In contrast, almost no new neutral species was found. This implies that Titan's dissociation chemistry takes place in the ionosphere rather than in the stratosphere. Understanding the chemical compositions of the "tholins" – these condensates issued from atmospheric dissociation and condensation – is critical for understanding Titan's atmospheric chemistry.

Titan' physical properties (mass, radius, density) lie between the ones of Ganymede and Callisto. One can thus wonder why Titan has a thick atmosphere while the other two satallites don't. The reason is probably the lower temperature formation of Titan (below 100 K). At such low temperatures, Titan's interior might have been composed of clathrates. A clathrate is a crystalline network of H_2O which is able to trap another foreign molecule (CH_4, NH_3, CO, Ar…). Titan's interior may have contained NH_3 and CH_4 in its clathrates. The outgassing NH_3 would have been later transformed into N_2 by photodissociation. However, these speculations remain to be confirmed. New space missions are presently under study, both at NASA and ESA, to pursue Titan's exploration of its atmosphere, surface and interior.

4.2.3 Triton

Triton, discovered in 1846 soon after Neptune, is on a retrograde orbit with high eccentricity, which suggests a capture origin. Triton's strong iclination, combined to Neptune's one with respect to the ecliptic, induces very strong seasonal variations of the subsolar point (from $+52°$ to $-52°$ latitude). Triton's atmosphere, revealed by Voyager 2's flyby in 1989, is nitrogen-rich, with a few percent CH_4, and its surface pressure is a few microbars. With a surface temperature of 38 K, Triton's surface is the coldest one ever measured in the solar system. The presence of a stable atmosphere, on such a small object, can be explained by the very low temperature which limits the gravitational escape. Voyager's images have revealed a rugged terrain in the southern hemisphere, with evidence for localized gaseous eruptions indicating cryovolcanism, probably due to nitrogen.

Near-infrared ground-based spectroscopy, performed in the late 1990s, has shown evidence for several types of ices at the surface of Triton: CH_4, N_2, CO, CO_2 and H_2O. This spectrum, as well as Triton's atmospheric composition, shows striking analogies with Pluto, which suggests a common origin. Triton could be a trans-neptunian object captured in Neptune's orbit, although the mechanisms of such capture are not fully understood presently. In any case, Triton appears as a precious link between the class of outer satellites and the one of trans-neptunian objects.

5 The new frontiers of the solar system

Many solar-system objects are now found beyond Neptune. Some, like Pluto and the comets, have been known for long. Others, the trans-neptunian objects, have been discovered since 1992.

The above-mentioned similarity between Triton and Pluto provides us with a natural transition between outer satellites and trans-neptunian objects which populate the Kuiper belt. The discovery of this new class of objects, over the past fifteen years, and the evidence that Pluto is only a representative of this family, have led the astronomical community to reconsider the status of Pluto and more generally, the definition of a planet. In August 2006, the International Astronomical Society has decided to remove Pluto from the official list of the solar-system planets which now include eight members, four terrestrial planets and four giant ones.

5.1 Pluto

Pluto, discovered by Clyde Tombaugh in 1930, is a small body, significantly smaller than the smallest planet Mercury, located beyond Neptune, at a semi-major axis of 39 AU, and characterized by a high eccentricity ($e = 0.25$). As a result, near perihelion, Pluto is closer to the Sun than Neptune itself: it has been the case between 1979 and 1998 which means that, during this period and still now, Pluto and Triton receive a comparable solar flux. This is the reason of the observed similarity between the two objects. Our knowledge of Pluto is mostly based on ground-based observations, and has largely benefited, since the 1980s, from two kinds of events: mutual occultations of Pluto and its satellite Charon, and stellar occultations. Additional informations have come from the HST, IRAS, ISO, and ground-based infrared spectroscopy.

Both Pluto and Triton have a N_2-enriched atmosphere with CH_4 at the percent level, with a surface pressure of a few microbars. The ices identified at the surface of Pluto are also very similar to the ones of Triton. The surface temperature of Pluto seems to be inhomogeneous, with parts as low as 40 K and others at 55 K (above the sublimation temperature of N_2). We must keep in mind that Pluto's atmosphere is stable only near perihelion: in the future, as the object moves toward aphelion (at 50 AU), le surface temperature will be too low for the ices to sublimize.

Pluto's satellite Charon, discovered in 1978, shows striking differences with both Pluto and Triton. Charon's density is lower, its albedo is also lower and its surface only shows the water ice signature. The formation of the Pluto-Charon system remains a mystery. As in the case of the Earth-Moon system, the low mass ratio of the two objects (8 for Pluto-Charon) suggests a formation following a major impact between Pluto and Charon's progenitor, both issued from the Kuiper belt.

5.2 The trans-neptunian objects

The existence of a family of small objects beyond Neptune was first proposed by Edgeworth and later by Kuiper before the middle of the XXth century, on the basis of theoretical arguments: the available mass of the protosolar disk beyond Neptune would have been too small to allow the formation of large planets, but the accretion processes should have led to the formation of many small bodies. The observational evidence, however, was possible only in the 1990s. As a result of a long search program, D. Jewitt and J. Luu discovered the first trans-neptunian object (TNO), 1992 QB1. In 2008, over 1200 TNOs have been discovered.

Based on their orbital properties, the TNOs belong to three distinct dynamical classes: (1) the classical objects (a majority of TNOs) which have low inclinations and low eccentricities; (2) the resonant objects, also called "Plutinos", with larger inclinations and eccentricities, are, like Pluto itself, in 3 :2 resonance with Neptune: their revolution period is 1.5 times the one of Neptune; (3) the "scattered" objects, with a perihelion beyond Neptune's orbit and a high eccentricity. A TNOs bigger than Pluto, 2003 UB313, also called Eris, has been discovered in this category.

Because TNOs are faint and distant objects, their physical properties are still poorly known. Combined observations in the visible and in the thermal range (with Spitzer in particular) have allowed to estimate the sizes and albedos of some objects. In some cases, satellites have been detected, allowing the determination of masses and densities. Near-infrared observations have revealed a wide variety of surface colors, suggesting the presence of water, methane, hydrocarbon and organic ices.

The present orbital distribution of the Kuiper belt is an important diagnostic of the dynamical history of the outer solar system. Numerical simulations performed by A. Morbidelli and his colleagues (the "Nice model") show that it can be explained as a result of the giant planets' migration (see 3.4). Most of the primordial population of the Kuiper belt was actually expelled out as Uranus and Neptune moved to their present position. This would explain why the estimated mass of the Kuiper belt today is only about one tenth of a terrestrial mass, while a much larger mass must have been initially requested to allow the accretion of TNOs over 100 km in size as observed today.

So far, TNOs have only been observed by remote sensing, from the ground or Earth orbit. The NASA mission New Horizons, launched in 2006, will encounter Pluto in 2015, and later another TNO, still to be selected.

5.3 Comets

Comets are known since Antiquity. Since Halley's work in the XVIIIth century, comets are known to be small icy objects, on very eccentric orbits, which spend most of their time at large heliocentric distances. When they approach the Sun, the surface of the nucleus sublimizes, leading to the outgassing of gas and dust, in the form of a coma and a dust trail. Comets then become visible in the sky, and their aspect may be spectacular. As first suggested by F. Whipple in 1950 in his "dirty snowball model", comets are mostly made of water ice.

Our knowledge of comets was first based on ground-based observations, in the UV and visible range. Early in the first part of the XXth century, spectroscopic measurements led to the detection of many radical and ions, products of the dissociation of the parent molecules present in the nucleus ices. The detection of the parent molecules became possible with the development of infrared and millimeter spectroscopy in the 1980s. This period coincides with the 1986 apparition of comet Halley, which was a major milestone for cometary physics: five spacecraft encountered the comet in March 1986 and a long-term ground-based monitoring was performed at all wavelengths over several years around perihelion. Another important milestone was the apparition of comet Hale-Bopp in 1997, an exceptionally big comet which was also monitored over several years.

5.3.1 The origin of comets

On the basis of a systematic study of cometary orbits, J. Oort, as early as 1950, found that most of the comets originate from a very distant reservoir (the Oort cloud) located at about 40000 UA. The comets could not have been formed there, because of the lack of available matter at such distance. So they must have been formed in the vicinity of Uranus and Neptune's orbits, and then expelled outward by planetary perturbations (mostly Jupiter's). The population of the Oort cloud is estimated to about 10^{11} comets. Occasionally, a comet from the Oort cloud, subject to local gravitational perturbations, is sent back toward the Sun and may be captured on a shorter periodic orbit, again by the effect of planetary perturbations. Oort cloud comets are characterized by random inclinations.

In addition to the Oort cloud population, there is another family of comets characterized by a low inclination. They are believed to originate from the Kuiper belt, between 30 and 100 UA. Some of them can be captured by Jupiter and become Jupiter-family comets. This is the case of comet Shoemaker-Levy 9 which was captured by Jupiter around 1930 and collided with the planet in 1994 (see 3.1).

5.3.2 The chemical composition of comets

With about 80% of the total mass, water is by far the main cometary constituent. About twenty other parent molecules have been discovered in comets, mostly throught their rotational millimeter transitions (Table 4). Water vapor was detected through its near-infrared band at 2.7 μm, both from the Vega spacecraft and the Kuiper Airborne Observatory. Other species, in particular CO_2 and hydrocarbons which have no dipole moment, have also been detected through

Table 4. Parent molecules in comets (after Encrenaz et al., 2004).

Molecule	Name	Abundance	Method of observation
H_2O	Water	100	IR, in situ
CO	Carbon monoxide	2–20	UV, IR, radio
CO_2	Carbon dioxide	2–6	IR
CH_4	Methane	0.6	IR
C_2H_6	Ethane	0.3	IR
C_2H_2	Acetylene	0.1	IR
H_2CO	Formaldehyde	0.05–4	IR, radio
CH_3OH	Methanol	1–7	IR, radio
HCOOH	Formic acid	0.1	Radio
HNCO	Isocyanid acid	0.07	Radio
NH_2CHO	Formamine	0.01	Radio
CH_3CHO	Acetaldehyde		Radio
$HCOOCH_3$	Methyl formiate	0.1	Radio
NH_3	Ammonia	0.5	IR, radio
HCN	Hydrogen cyanide	0.1–0.2	IR, radio
HNC	Hydrogen isocyanide	0.01	Radio
CH_3CN	Cyanomethane	0.02	Radio
HC_3N	Cyanocetylene	0.02	Radio
N_2	Nitrogen	0.02–0.2	Visible (from N_2^+)
H_2S	Hydrogen sulphide	0.3–.5	Radio
H_2CS	Thioformaldehyde	0.02	Radio
CS_2	Carbon disulphide	0.1	UV (from CS), radio
OCS	Carnonyl sulphide	0.4	IR, radio
SO_2	Sulphur dioxide	0.2	Radio
S_2	Sulphur	0.05	UV

their infrared transitions, excited through resonent fluorescence by the solar flux. Complex hydrocarbon molecules, including saturated and unsaturated chains and possibly aromatics, have been also detected in the near-infrared range. In the solid phase, silicates have been identified through their infrared signatures around 10 μm. It is striking to note that all gaseous species identified in comets have also been identified in the interstellar medium, which favors a clear link between interstellar and cometary matter.

As in the case of the giant planets, the D/H ratio is a precious diagnostic of the conditions and processes of cometary formation. D/H is not measured from HD/H_2 or CH_3D/CH_4, as in giant planets, but in HDO/H_2O, as water is the main cometary constituent. HDO transitions are best measured in the sumillimeter range, while H_2O can be inferred from the radio monitoring of OH. In addition, an in-situ measurement was obtained in the case of comet Halley. Three measurements have been performed so far, on 3 Oort-cloud comets (Halley, Hyakutake, Hale-Bopp). All three measurements indicate a value of $3 \cdot 10^{-4}$, i.e. an increase by a factor 2 relative to the SMOW (terrestrial) value. An immediate conclusion seems to be that the terrestrial oceans cannot have been completely made of cometary water ; indeed, the D/H of the Earth rather fits the one of D-type asteroids from the outer main asteroidal belt, which could be the main source for terrestrial water.

5.3.3 Open questions and future exploration

Most of the well-known comets are Oort comets, because they are brighter and easier to observe. An important question for future cometary exploration is whether Kuiper-belt comets have the same chemical composition as the Oort-cloud comets. In particular the determination of the D/H ratio in Kuiper-belt comets will be a key diagnostic of the conditions where they formed.

The European mission Rosetta, launched in 2004, will encounter comet Churuymov-Gerasimenko in 2014, at a distance of 3 AUs. An orbiter will monitor the onset and development on the cometary activity, while a descent probe will land on the nucleus for in-situ measurements. Among the key questions are the search for prebiotic molecules and amino-acids, such as those discovered in some primitive meteorites like Murchison.

6 Outer planetary systems

We have seen that the outer solar system includes several classes of objects, from the biggest (giant planets) to the smallest ones (comets). One can wonder if some of these bodies could be observable in other planetary systems.

Detecting giant exoplanets distant from their stars is within today's capabilities, and is starting to be done. What is required is a large database extending over time periods longer than ten years. As the first exoplanet's discovery was made in 1995, such data bases are presently beeing built up.

Outer satellites around giant exoplanets have not been observed so far, but could in principle be detected either by the transit or the microlensing technique. The COROT database will possibly provide new results in this respect.

Comets have been already detected in a protoplanetary disk, the one of Beta Pictoris. Actually it is not a protoplanetary disk but rather a debris disk. The presence of a planet is strongly suspected as being responsible for the observed gap within the disk. Comets were identified as being responsible for transient variations in the UV spectra as they fell toward the central star. The same phenomenon might be observable on other protoplanetary or debris disk.

Finally, the Kuiper belt of a planetary system might become detectable in the case of an evolved star. Such an event was reported in the case of the late star W Hya, for which the submillimeter satellite Odin detected, in the 557 GHz water transition, a large excess of water vapor. It was suggested that such excess was due to the sublimation of the Kuiper belt, as the star evolved into a red giant and heated up its environment. This is the scenario which is expected to happen to the solar system in the far future, some 5 billion years from now...

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