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Satellites and Rings of the Giant Planets

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1.1. Introduction

Ground-based measurements as well as measurements from the Voyager, Galileo, and Cassini-Huygens probes have shown that the icy satellites around the giant planets (see Figure 1.1) are not the dead and lifeless objects that scientists imagined until the beginning of the 2000s. Recent observations have in fact revealed that they are unique and active worlds with, for some, surprisingly diverse characteristics on the surface and in the thin atmospheres (Schenk 2010; Lang 2011; Catling and Kasting 2017).

Until the 1990s, our knowledge of the Solar System was based on the data collected by the Voyager missions, two NASA probes launched in 1977 that flew by the Solar system's giant planets in the 1980s as well as by 48 of their satellites out of the 200 or so that have been observed to date (Atreya *et al.* 1989).[1]

The Galileo mission, developed by NASA, had the goal of studying the planet Jupiter and its satellites. Launched in 1989 and in operation until 2003, Galileo allowed us to better characterize Jupiter's atmosphere, its magnetosphere, and its

1 See also: https://voyager.jpl.nasa.gov/.

The Solar System 2,
coordinated by Thérèse ENCRENAZ and James LEQUEUX. © ISTE Ltd 2021.

large satellites.[2] Most notably, it provided new information about volcanism on Io, as well as substantial evidence about the presence of a liquid water ocean under the frozen surface of Europa and the presence of a magnetic field on Ganymede.

The ESA-NASA-ASI Cassini-Huygens mission, launched in 1997, included an orbiter (Cassini) for Saturn and a lander (Huygens) for Titan. It arrived in the Saturn system in 2004 (Coustenis 2015). For 13 years (2004–2017), it studied the Saturnian environment and unveiled details about the planet, its satellites, and its rings. The satellite Titan was the target of the European Huygens probe, which landed in January 2005. The mission instruments provided an impressive wealth of data that revolutionized our knowledge of the Saturn[3] system.

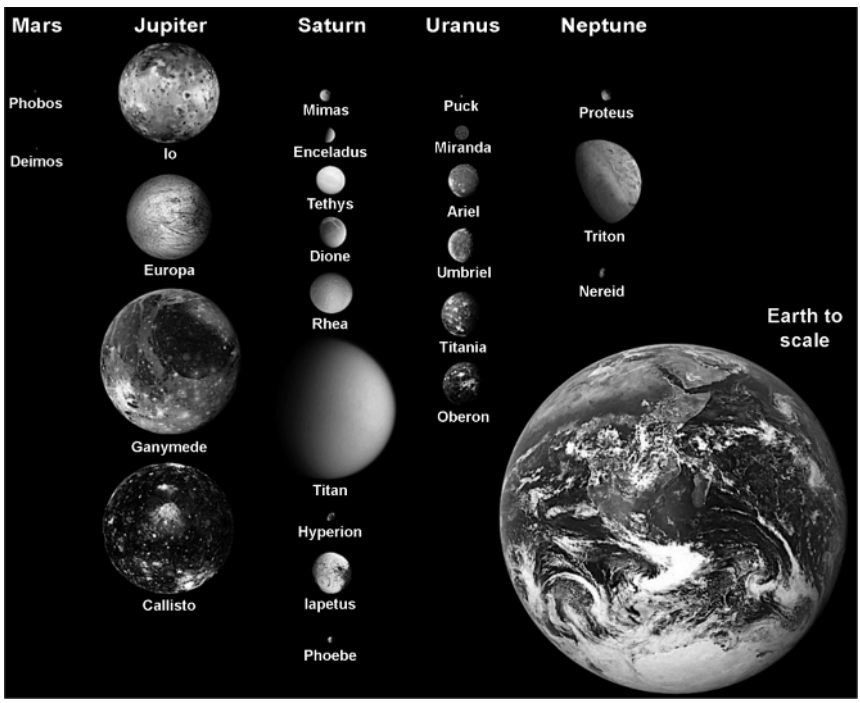


Figure 1.1. *Main satellites of the Solar system at scale (source: Wikimedia Commons, Bricktop, Deuar, KFP, TotoBaggins, City303, JCPagc2015). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

2 See also: https://www.jpl.nasa.gov/missions/galileo/.

3 See also: https://www.jpl.nasa.gov/missions/cassini-huygens/.

Most satellites are made up of a mixture of water and other kinds of ice, including, often, ammonia ice and rocky material (Atreya *et al.* 1989). A surprising variety of unusual and spectacular geological characteristics have been observed on these satellites, including patterns that bear witness to tectonic activity, volcanism, resurfacing, and more. Manifestations of geological and atmospheric processes that occur on our planet have also been observed, helping us to improve our understanding of the formation, evolution, and conditions for life in our Solar System and beyond. The latter presuppose the presence of liquid water for around a billion years, as well as the presence of chemical elements that are essential for life (referred to as "CHNOPS," for carbon C, hydrogen H, nitrogen N, oxygen O, phosphorus P, and sulfur S) and of sources of energy in a stable environment (Lissauer and de Pater 2019). According to a categorization proposed several years ago, there are two kinds of possible habitats: those in which underground oceans of water interact directly with a core rich in silicate, as on Europa, the smallest of Jupiter's Galilean satellites, or on Enceladus, a small satellite orbiting Saturn, while another class of habitats includes satellites that have bodies of liquid water sandwiched between two layers of ice, as we expect to be the case for Ganymede, the largest satellite in the Solar system, in orbit around Jupiter or Titan, Saturn's largest satellite (Coustenis and Encrenaz 2013; Coustenis 2014; Hand *et al*. 2020).

We know that the large satellites of the gas giants, which are located beyond the "ice line" (that is, the distance from the Sun corresponding to the limit for which condensation of water molecules is possible on the surface of a celestial body), contain large amounts of water. Indeed, with an average density of around 1.8 g/cm^3, the largest satellites (like Titan) contain almost 45% water by mass. Among these satellites, some have a core rich in silicates and can contain underground oceans of liquid water in contact with the core (as is probably the case for Europa and Enceladus). This is important, because in such environments on Earth, we find life (for instance, in the hydrothermal vents located at the bottom of the oceans) and therefore generate the heat from the chemical sources located under their ice crust. Other satellites can have oceans or pockets of liquid water trapped between two layers of ice (as suggested by measurements on Ganymede and Titan). In the study of the emergence of the elements of life on such satellites, the time scale is essential. If this liquid environment lasted for long enough, it could see the emergence of life; but, on the other hand, this could be inhibited if the ocean was so isolated from the environment that it was impossible for the concentration of ingredients necessary for life or the appropriate chemical inventory for the pertinent biochemical reactions to occur. What is important is to realize that these satellites contain large volumes of water, from whence they get their nickname of "ocean worlds" (see Figure 1.2). Sometimes the amount of water contained in these satellites exceeds that found on

Earth, sometimes by factors that can even reach an order of magnitude, as is the case for Titan and Ganymede.

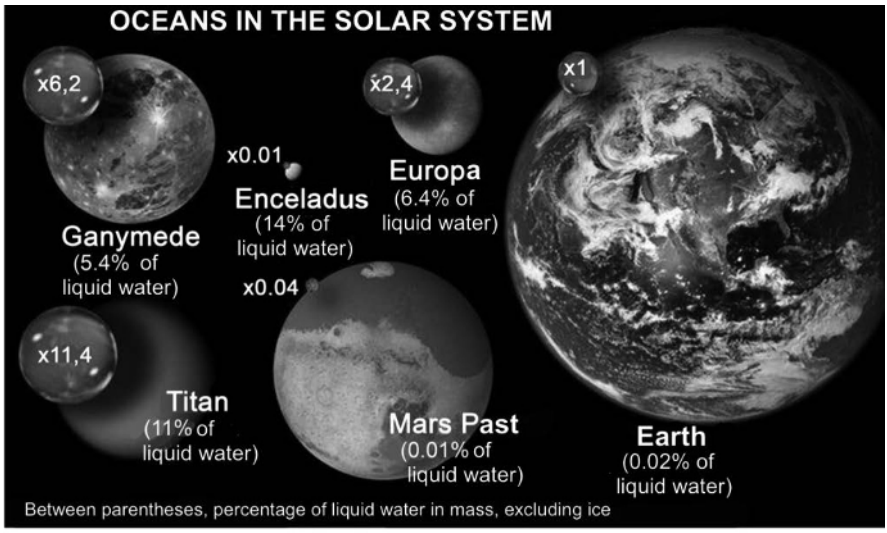


Figure 1.2. *Ocean worlds in the Solar system. The mass of the water in liquid or solid form is indicated, the mass of water on Earth taken as a unit. The percentage of liquid water in relation to the total mass of the planet or satellite is also given (source: PHL@UPR Arecibo, NASA). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

However, the exploration of these sub-surface oceans isn't easy, because the outer layers of ice on satellites can be very thick. We suppose that their thickness is on the order of several hundreds of kilometers on Ganymede, Callisto, and Titan. Europa may have a thinner layer of ice (possibly several dozens of km) because its proportion of water is only 10% of its mass, and it also has "chaotic" regions where the surface layer of ice may be even thinner. To understand the internal structure of the water layer, it is necessary to know the phase diagram of water under certain conditions of pressure and temperature.

On the edge of our Solar System, we find Uranus and Neptune surrounded by satellites that are unique in many ways, such as Triton and its geysers. Triton (in orbit around Neptune) and other objects beyond Neptune's orbit are thought to harbor liquid water oceans under the surface (still present today, even at the very

low temperatures of their environments). The satellites of Uranus and Neptune have only been explored to date by the Voyager 2[4] mission.

Below, the most important discoveries about the outer Solar System's satellites from spatial and ground-based observations are described.

1.2. Jupiter's satellites

As of 2020, we are aware of 79 natural satellites around Jupiter (see Table 1.3, Volume 1, and Figure 1.1 in this volume) with diverse characteristics (Burns *et al*. 2004; Schenk 2010). The four largest satellites in the system, called the "Galileans" (Io, Europa, Ganymede, and Callisto) were discovered by Galileo in 1610.

1.2.1. *The Galilean satellites*

Among the Galilean satellites, Ganymede, Europa, and Io are caught in a 1:2:4 orbital resonance, which means that these objects periodically exercise strong gravitational influence on each other (see section 1.2.3, Volume 1, and section 4.5 in this volume). The three ice-covered Galilean satellites, Callisto, Ganymede, and Europa, present a wide diversity of characteristics on their surfaces, probably because of their different evolutions, even if they are situated in the same environment (see Figure 1.1). The unique characteristics of their geology bear witness to the parameters of their formation such as composition, density, and temperature, as well as evolving factors such as geophysical processes and the stage of differentiation (Schenk 2010). The Galilean satellites show signs of increased geological activity as their distance from Jupiter decreases (see Figure 1.3). As early as the 1980s, the observations from the Voyager probe showed large disparities between these four satellites, suggesting a strong influence of gravitational tidal forces on each of them. Thus, Io, the closest to Jupiter, is subjected to enormous tidal forces that lead to very intense volcanism. Europa may still be very active tectonically and volcanically today, because the small number of craters detected indicates a relatively young surface, while the larger Galilean satellites, Ganymede and Callisto, which are also the farthest, have old and densely cratered surfaces with a large range of sizes and internal structures (see Figure 1.3). Furthermore, the interactions with the Jovian magnetosphere and stellar winds, as well as the effects of the tides, have left traces on the surfaces that we see today in the form of æolian processes, cryovolcanism, and impact craters.

4 See also: https://solarsystem.nasa.gov/missions/voyager-2/in-depth/.

Understanding the gravitational interactions between Jupiter and the Galilean satellites is essential for a number of aspects of the science of the system of Jupiter, including habitability, because of their influence on the evolution of the interior and the surface of a satellite ((Burns *et al.* 2004; Lissauer and de Pater 2019); see also Figure 1.3). In particular, the effect of Laplace resonance can be decisive for the subterranean oceans of Europa and Ganymede, as well as for the future of volcanism on Io, where tidal dissipation is a significant source of heat, as it is for the other satellites.

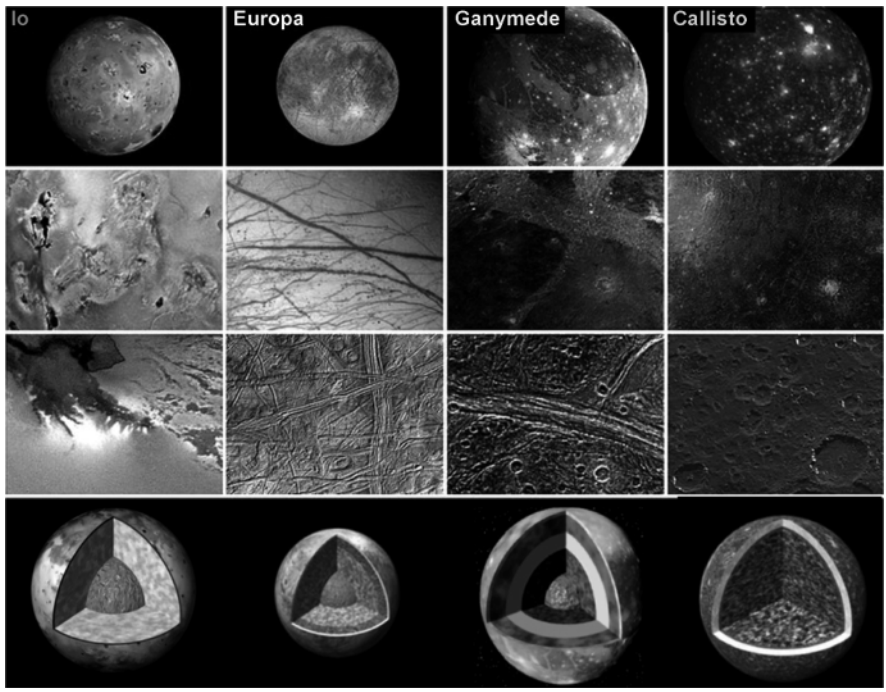


Figure 1.3. *The Galilean satellites of Jupiter, aspects of their surface and their internal structure; from left to right (as a function of their distance from Jupiter): Io, Europa, Ganymede, and Callisto, with their sizes at scale (source: JPL NASA). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

There is substantial proof that layers of ice and liquid exist on these satellites, but there is no certainty about their composition or their exact extent (Schenk 2010). On Ganymede, gravimetric data indicates a completely differentiated structure. A liquid layer as thick as 100 km in some places is trapped between the icy crust above and a layer below composed of ice at high pressure, which does not exist in natural

environments on Earth. Europa has a similar internal structure. We think it has a metallic core and a layer of silicates, about the same size as the one on Ganymede, but a thinner hydrosphere that is no thicker than 100 km at its maximum. The biggest difference here is that, in the case of Europa, the liquid layer is almost certainly in direct contact with the silicate mantle. Callisto is very similar to Ganymede, although it is not completely differentiated and does not have an intrinsic magnetic field. This lack of differentiation, which is surprising for a body of its size, may be due to the fact that Callisto is not in resonance with the other Galilean satellites (see section 1.2.3, Volume 1 and section 4.4 in this work), which is one of the most striking pieces of evidence of the complexity of the interaction process in the Jovian system. Its surface is very old and highly cratered and, finally, it has a deep ocean similar to the one on Ganymede.

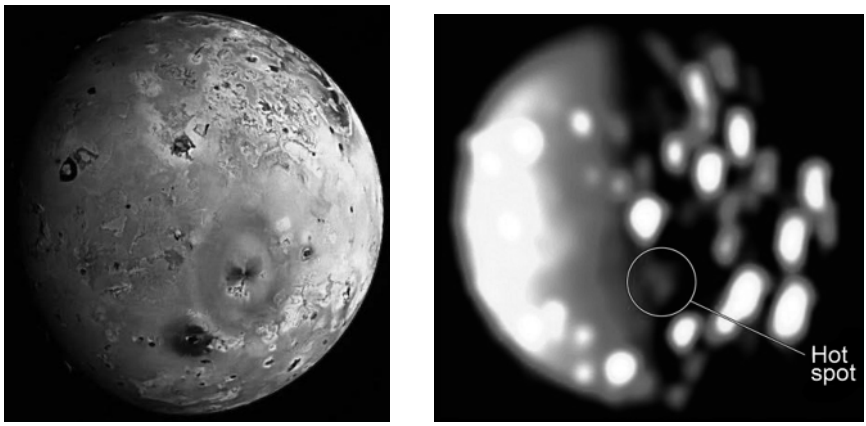
Observations indicate that the water under the surface is very probably mixed with other components such as salt hydrates or carbon dioxide, which we find on the surface of most of the Galilean satellites. Apart from the biochemical components that are necessary for life, other elements such as sodium, magnesium, calcium, iron, and potassium play an important role. However, while these components may be present on a surface, the conditions for their survival on Europa are not the same as on Ganymede, because their distance from the planet and hence the quantity of radiation of ions and electrons they receive are very different. Close to Jupiter, as in the case of Europa, this radiation is extremely harmful and probably deadly for any organic product present, preventing the survival of oxidants and organics on the surface for very long. To preserve Europa's potential habitability, these molecules would have to be able to enter the liquid water ocean under the surface. The composition of the surface of the Galilean satellites is largely reflected in their thin atmospheres (and exospheres), observed primarily in the UV from space and from the ground, atmospheres that result from the pulverization and sublimation of the substances on the surface. Conversely, the atmospheric components influence the surface composition. Europa has a dioxygen atmosphere with traces of sodium and potassium. Ganymede also has a thin oxygen atmosphere and a hydrogen exosphere. The intrinsic magnetic field around Ganymede is precious for habitability, because (as on Earth), it prevents high-energy particles from hitting the satellite.

1.2.1.1. *Io*

Io is the third largest of the Galilean satellites; a bit larger than our Moon, it is the closest to Jupiter (orbit at 6 Jovian radii), which exerts enormous tidal forces that lead to impressive geological and tectonic activity. One way in which this activity manifests is the presence of at least 250 volcanoes whose eruptions eject the gases, primarily sulfur dioxide, that create its thin atmosphere, which extends more than

300 km into space. Ionized particles are torn from Io because of its interaction with Jupiter's magnetosphere, forming a fairly substantial torus that can be detected in the UV (Catling and Kasting 2017).

The surface of Io shows a great variety of terrains, with many volcanic vents as well as non-volcanic mountains, calderas that are several kilometers deep, lakes of molten sulfur, and other patterns that give it its highly contrasted coloration, ranging from white to red and from green to orange (see Figure 1.4). The absence of impact craters on the surface indicates that it is young and is constantly being renewed by this intense activity (Schenk 2010).



a) b)

Figure 1.4. *Io. For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

COMMENTS ON FIGURE 1.4.– *(a) Composite color image of Io taken by the Galileo probe, showing the satellite's topography: volcanoes such as Loki Patera (the large dark horseshoe near the terminator), mountains, and plateaus can be seen. The large orange ring in the lower right is formed by matter deposited during eruptions of the largest volcano, Pele (source: NASA/JPL/University of Arizona). (b) Taken in 2018 by the Juno probe, this infrared image shows the location of a new hot spot on Io's southern hemisphere (source: NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM).*

The interior of Io is composed of a liquid iron core surrounded by a mantle made up of molten silicates enriched with sulfuric matter (see Figure 1.3). An extremely hot ocean of magma (1,500 K, approximately) that is 50 km thick is located at a depth of 30 or 50 km under Io's surface. Above this, the satellite's crust is very thin, and its morphology varies as a function of geologic activity.

1.2.1.2. *Europa*

Europa is the smallest of the four Galilean satellites in orbit around Jupiter ((Schenk 2010); see also Table 1.3, Volume 1). With a diameter of 3,140 km, Europa is slightly smaller than our Moon. Its distance from Jupiter is about 9.5 Jovian radii. Its density is 3.0 g/cm^3, which is typical for a mixture of rocks and ice. Its high albedo (0.67) suggests that its surface is primarily made up of water ice. Europa's surface temperature ranges from about ~125 K at the equator to ~50 K at the poles.

The spatial exploration of Europa began with the Voyager 2 encounter in 1979. Voyager's camera revealed an interesting surface topography made up of low-relief crests and chaotic terrains with few impact craters (Pappalardo *et al.* 2009). The pattern of crests already seemed to indicate that the icy crust was detached from the interior and moves slightly in relation to it. Europa thus became a privileged target for the Galileo mission, which approached Jupiter in 1995 and explored the Jovian system until 2003. Information was collected about the surface characteristics, the internal structure, and Europa's interaction with Jupiter's magnetosphere ((Burns 2004); see also Figure 1.3).

Among the most striking features of the observed surface of Europa are the dark streaks, called *linae*, which encircle the entire globe (see section 5.3.3 and Figure 5.9). They are countless, overlapping, and measure up to 1,000 km long and 1 km deep, but their edges never rise more than a few hundred meters high. In many cases, the crests are doubled, often with dark exterior borders and a central band. The images show that on each side of the lines, the edges are shifted with respect to each other (see Figure 1.3). These *linae*, probably of cryovolcanic origin, are interpreted as being the result of eruptions of hot water in a scenario that is similar to the one for terrestrial ocean ridges. Moreover, the fracture structures on the surface of Europa are different from those we would expect in the case of a completely solid object. Both recent and ancient fractures present different orientations, the more varied the older they are. This scheme suggests that the surface of Europa turns slightly faster than the sub-surface substances, which implies a liquid or viscous subsurface.

The surface of Europa also shows fractured and chaotic terrains called *lenticulae*, whose diameter varies from 10 to 100 km. There are many domes that seem to have been pushed out from the interior. These domes can be formed by the ascent of hot water between the cold ice of the exterior crust, in a scenario reminiscent of Earth's magma chambers. There are relatively few impact craters, which indicates that the surface of Europa is young. Its age can be estimated on the basis of the number of comets and asteroids in Jupiter's vicinity. This assessment results in an age of about

100 to 300 million years, which is a very short period of time compared to the satellite's history. Quite probably, Europa is still geologically active today.

It is now generally accepted that there is a water ocean under the icy crust of Europa ((Pappalardo *et al.* 2009; Hand *et al.* 2020); see also Figure 1.5). This ocean supplies the best explanation of the characteristics observed on the surface: *linae*, lenticular domes, fracture structures. In 2000, another discovery supported the ocean hypothesis: Galileo's magnetometer detected a weak magnetic moment, induced by the variable portion of Jupiter's magnetic field. The existence of this magnetic field requires the presence of a substance that is highly electrically conductive in the satellite's interior. The most plausible candidate is a large layer of liquid salt water under the surface. Spectral analysis of the dark surface characteristics should make it possible to detect the presence of salts in this ocean. Magnesium sulfate and sulfuric acid are possible candidates; sulfur components could explain the reddish color of the stripes.

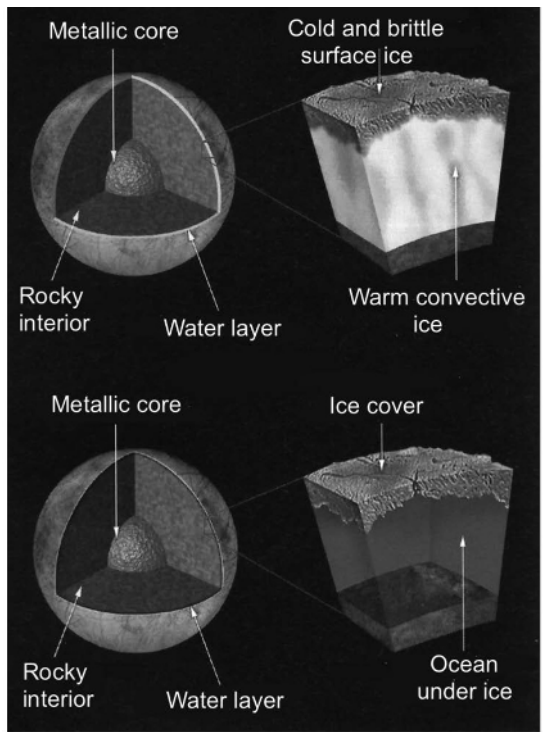


Figure 1.5. *Models of the interior of Europa with the presence of a liquid or ice ocean (source: NASA). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

The supposed existence of an underground ocean clearly depends on the capability of maintaining liquid water in the interior. What source of internal energy maintains the water at the right temperature on Europa? Radioactive heating is not sufficient because the volume/radius relationship is much smaller than on Earth. On the other hand, tidal heating is a plausible source of energy. Europa is known for being strongly differentiated, with a central core of iron and iron sulfide, surrounded by a mantle of silicate and then water (see Figure 1.5). Without the tidal effect, the water would be in its solid state. We have seen that Europa is in orbital resonance with Io and Ganymede. As a result, although it is in synchronous rotation with Jupiter, the bulge raised by Jupiter changes slightly in size and orientation under the effect of the other satellites when Europa moves along its orbit, causing a difference of 3 km between the radii in the radial and perpendicular directions, which leads to energy dissipation. According to models, this reaches its maximum effect in the lower part of the ice layer. In 2008, scientists proposed that another source of potentially more efficient energy could come from large planetary tides, generated by Rossby waves, as a result of the satellite's non-zero axis obliquity (Schenk 2010).

Furthermore, in 1995, observations from the Hubble Space Telescope revealed that Europa had a very tenuous atmosphere composed primarily of molecular oxygen, O_2, with a surface pressure of about 0.1 μPa, or 10^{-12} bars (Catling and Kasting 2017). Molecular oxygen is the primary atmospheric component because it does not freeze. Two years later, the Galileo probe also identified a tenuous ionosphere resulting from the interaction of Europa's surface with the high-energy particles of the Jovian magnetosphere. This magnetosphere contains a dense, high-energy plasma of oxygen and sulfur ions that escaped from Io. Thus, the surface of Europa is subjected to an intense bombardment of energetic particles from Jupiter's radiation belts, which leads to the rupture of water molecules and the generation of hydrogen peroxide, H_2O_2, a powerful oxidant that can be a chemical source of energy. Indeed H_2O_2 has a tendency to decompose exothermically into water and oxygen. It has been detected on the surface of Europa in the infrared and ultraviolet spectra. Europa's trailing hemisphere is particularly exposed to this effect, as shown by the black substance on the surface, interpreted as being a result of sulfur polymers altered by radiolysis. Colliding ions eject water molecules from the surface of Europa (this is the *pulverization effect*). Thus, the surface is slowly eroding: the rate of erosion is estimated at around 5–20 cm per million years. This provides additional evidence that the surface of Europa is relatively young. The Galileo probe's infrared spectrometer also detected mixtures of hydrated sulfuric acid and hydrogen peroxide, which could explain some of the surface's spectral characteristics. Molecular hydrogen cannot exist on Europa's surface because the satellite's gravitational field is too weak. It escapes, along with atomic and molecular oxygen, to form a neutral torus along the length of Europa's orbit. This

torus was identified by the Galileo and Cassini probes. The question of the presence of convection in Europa's icy crust, which is likely to permit an exchange of matter between the surface and the ocean, remains open in the thin crust model because of the large number of tectonic characteristics such as fissures and visible faults on the surface (see Figure 1.5).

In 2016, water plumes were detected episodically on Europa by the HST, which may indicate cryovolcanic activity, as on Saturn's satellite Enceladus. In 2018, the results were confirmed by reanalyzing Galileo data from 1997, which provided new proof of the presence of an ocean of water below the icy crust.

How thick could the ice crust on Europa be? According to models, it could vary between several kilometers and a few dozen kilometers. The study of the largest craters on Europa, surrounded by concentric rings and filled with flat, fresh ice, suggests an icy crust that is 10 to 30 km thick, including a layer of warm, ductile ice above a liquid ocean that is about 100 km deep. We have seen that, according to some models of the internal structure, the liquid ocean should be in direct contact with the silicate mantle. The reanalysis of images from Galileo of chaotic terrains suggests that these areas form above pockets of liquid water located in an icy shell that is 3 km deep. While drilling 3 km down into Europa's surface is currently beyond our capabilities, this result, if confirmed, would have major consequences for astrobiology (Coustenis and Encrenaz 2013; Hand *et al.* 2020).

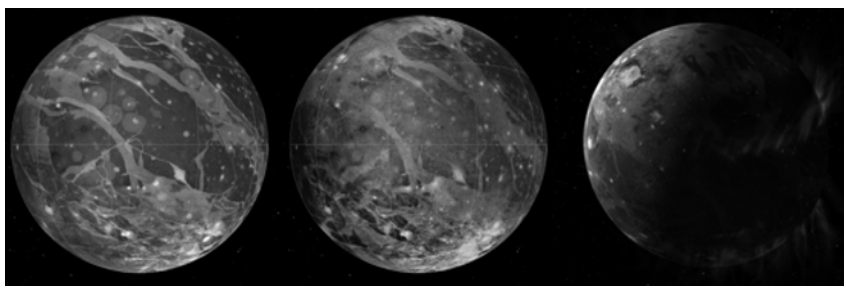
The determination of the topography of the surface and the internal structure at the interface between the silicate core and the liquid, as well as the detection of potential anomalies of mass at this location, will allow us to confirm the hypothesis that volcanism and/or hydrothermal activity could exist or have existed on Europa, as with the central ocean ridges on Earth. Such activity would release a variety of organic components into the ocean that are essential to maintaining simple forms of life at the bottom of the ocean, like those discovered around deep hydrothermal springs on Earth three decades ago. Concerning energy sources, the presence of an oxidizing agent on the surface, H_2O_2, and a reducing agent at the bottom of the ocean in the presence of hydrothermal activity introduces the possibility of a redox couple active on an oceanic scale. But this only works if the surface oxidants can supply the ocean through an icy crust that could be partially permeable. Subsequent exploration of Europa *in situ* by an orbiter and, even better (when the technology becomes available), by a lander, is necessary to confirm or to disprove these ideas.

1.2.1.3. *Ganymede*

Ganymede is in several ways a unique satellite in the Solar System because of its size (5,628 km in diameter), its intrinsic magnetic field, and its geological

characteristics (Atreya 1989; Burns *et al.* 2004; Schenk 2010). Orbiting at about 15 Jovian radii, the largest satellite in the Solar system (larger than the planet Mercury) has a very thin atmosphere, which was detected by the HST in 1995. It is essentially composed of O_2, which is ionized by impacts of electrons to form atomic oxygen O, and probably also ozone O_3, as well as a small proportion of atomic hydrogen. The surface pressure is less than 1.5 μPa.

Its albedo (0.43) is compatible with the presence of water ice everywhere on the surface, on which two main types of terrain are distinguished. Ganymede thus occupies a key position in terms of geological evolution because it presents an old and dense terrain, like many of the terrains on Callisto, but also wide regions of tectonic resurfacing, similar to most of the surface of Europa (see Figure 1.3). One third of its surface is composed of old, dark regions that contain many craters formed four billion years ago. The other two thirds are more recent, lighter regions that probably indicate a process of resurfacing, forming a network and crisscrossed by large grooves and ridges (see Figure 1.6). The reason for this difference is not well understood; it may be the result of tectonic activity due to tidal heating. Hydrated minerals have been detected on Ganymede's trailing hemisphere (itself in synchronous rotation around Jupiter). Furthermore, various substances other than water ice have been identified on Ganymede's surface based on data from Galileo and from ground-based observations: carbon dioxide, sulfur dioxide, molecular oxygen, ozone, and various organic components probably formed locally thanks to the same process of radiolysis as on Europa (see Figure 1.6).



a) b) c)

Figure 1.6. *(a) Global geographical map of Ganymede; (b) mosaic of images of Ganymede; (c) illustration of the auroras on Ganymede (source: USGS Astrogeology Science Center/Wheaton/NASA/JPL-Caltech, ESA, G. Bacon (STScI)). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

The satellite's density (1,936 g/cm^3) indicates that it is made up of equal parts of water ice and rock. The observations show that it is a completely differentiated

body, with a hydrosphere of at least 500 km representing 50% of the satellite's mass, a silicate mantle, and an iron core. Ganymede is one of only three solid bodies in the entire Solar System that possess an intrinsic magnetic field generated by a dynamo effect (the others are Mercury and Earth). Ganymede's magnetic field is in turn anchored in the enormous Jovian magnetosphere (Burns *et al.* 2004). Finally, it also possesses an induced magnetic field generated by currents circulating in a conductive liquid, which suggests the presence of a salty liquid ocean under the surface (see Figure 1.3). As a result of Ganymede's movement through Jupiter's magnetosphere, the auroral ovals that encircle the satellite should oscillate with an amplitude of 6° (see Figure 1.6). But if there is a large ocean in the depths of Ganymede, acting as a conductive environment, induction should produce an electrical field that in turn generates the satellite's magnetic field observed by Galileo and that could also reduce the amplitude of the oscillations of the auroral ovals. These ovals and their positions were measured by Hubble's UV instruments in 2017 and were found to be 2° instead of the 6° that was expected, leading to a strong argument in support of the existence of a liquid salty ocean in Ganymede's interior (Hand *et al.* 2020). We do not currently know if exchange processes are possible between the silicates and the salt ocean, which is presumed to lie almost 200 km below the surface of Ganymede, sandwiched between layers of ice.

With the various processes that leave their marks on its atmosphere (notably the presence of O, O_2, and possibly O_3) and its surface (such as tectonics, crater formation, and cryovolcanism), Ganymede is an archetype that allows us to understand a number of the processes that affect icy satellites throughout the outer Solar System and in some exoplanetary systems, those of the "ocean worlds," with very different properties from terrestrial planets but that nevertheless qualify for habitability.

1.2.1.4. *Callisto*

Callisto has a diameter of about 4,800 km and orbits Jupiter at an average distance of about 27 Jovian radii. Its density (1.83 gcm^{-3}) indicates that Callisto is made up of about half rock and half ice. Unlike the other Galilean satellites, its surface is dark, uniform, and completely covered with impact craters ((Schenk 2010); see also Figure 1.3). Callisto is the Galilean satellite that is farthest from Jupiter, and it is thus subjected to weaker tidal forces than the others, leading to a surface that has not been renewed by internal processes. The density of craters indicates that they were produced about 4 billion years ago, when all of the Solar System's bodies were subjected to heavy bombardment by comets and meteors. In addition to its large number of intermediate-sized craters, the surface of Callisto shows structures surrounded by rings that measure between hundreds and thousands of kilometers in diameter, likely created by major impacts. The largest, named

Valhalla, contains about 10 concentric rings with a maximum diameter of about 3,000 km. The preservation of this evidence of intense bombardment on the surface of Callisto is compatible with the lack of internal differentiation, which confirms the spatial measurements of its gravity field. Its interior is thus made up of well-mixed rock and ice, rather than presenting the core-mantle structure found on Io, Europa, and Ganymede. This satellite, alone among the Galilean satellites, has never been trapped in the orbital resonances responsible for tidal heating, which were so important in the evolution of Ganymede, Europa, and Io. Internal activity therefore did not noticeably modify Callisto's surface as it did on the other Galilean satellites. Nevertheless, Callisto has a weak magnetic field induced by Jupiter's field, which raises the possibility that a conductive layer of liquid salt water exists somewhere under its surface.

Unlike Ganymede, Callisto does not show large amounts of ice on its surface. The near-infrared spectra only contain weak indications of water ice, and the surface is much too dark to be made up exclusively of ice. The detailed images from Galileo reveal that the deposits of dark matter erased the smallest craters in certain areas (see Figure 1.3), and spectroscopic observations show that the substance is a mix of hydrated minerals that resemble clay and solid carbon dioxide. Spectroscopic studies have also shown the existence of a thin atmosphere composed primarily of carbon dioxide constantly escaping from the ground, traces of sulfur compounds (which may come from Io via volcanic eruptions), hydrogen peroxide (which is probably produced from water ice by photochemical reactions), and organic compounds potentially brought there by comets.

1.2.1.5. *Current and future exploration of the Galilean satellites*

The value of more thorough exploration of the giant planets and their systems became obvious following the discoveries made by the Voyager and Galileo missions. We currently have a mission exploring the Jovian system, the Juno probe from NASA, which was launched on August 5, 2011 and which has been on site since 2016, but this mission is essentially dedicated to the study of the giant gas planet, its magnetosphere, its formation, and its evolution, while the study of the satellites is *a priori* limited to their interactions with the planet's magnetic field.

In the preceding discussion, we demonstrated the interest of exploring the unique worlds that are the satellites of the giant planets and their potential habitats. One of the main objectives of the coming missions will be to determine the quantity of water present in the Jovian system, its distribution, and its potential contents in terms of organic material on and under the surface of the icy satellites, as well as the

method of transport for substances between satellites through volcanism, pulverization, and impacts.

The Juice mission (*JUpiter ICy moons Explorer*) was chosen by ESA in 2013 as the first large mission in the 2015–2025 Cosmic Vision program. It was designed as a follow-up to the measurements taken by the Galileo mission, aiming to study in depth the system of Jupiter and its satellites, by concentrating on the largest, Ganymede. Juice's main theme is "the emergence of habitable worlds around gas giants", taking into account the necessary conditions implying the simultaneous presence of organic compounds, oligo-elements, liquid water, sources of energy, and relative stability of the environment over time.

The Juice mission is expected to launch in 2022 and arrive at Jupiter in 2031. The nominal mission should last for about 3.5 years. The mission scenario is designed to permit Juice to carry out an exploration of the Jovian system with the help of gravimetric assistance from the Galilean satellites to determine its trajectory. This exploration will include continuous surveillance of the magnetosphere and atmosphere of Jupiter, two flybys of Europa, and a flyby phase of Callisto on a trajectory that will reach 30° of latitude above Jupiter, culminating with a phase in orbit around Ganymede at 500 km from the surface, and possibly then even lower. The expected end of mission scenario involves crashing the spacecraft into Ganymede. The craft includes 10 instruments[5] and radio and Doppler experiments. The Juice mission will thus provide important information by establishing the existence of oceans below the surface of the crust of Ganymede, Europa, and Callisto, and by defining their main characteristics. For Europa, the Juice mission has planned two flybys above what we think are regions that were recently or are currently active and covered with thin layers of ice (regions referred to as "chaotic"), with the goal of extracting information about the underlying liquid ocean, its extent, and its composition. Observations will also be carried out on Io and other smaller satellites.

For technical and budgetary reasons, a surface lander or penetrator able to carry out a characterization *in situ* of the surface ice on Europa is not possible for now, nor is a dedicated orbiter, because of the high level of radiation generated by Jupiter's magnetic field. As a result, the characterization of the depth and breadth of Europa's ocean and of the boundary of its interface with the silicate mantle will be undertaken by Juice and a NASA mission specifically designed to study Europa, called Europa-Clipper. The latter is expected to launch in the mid-2020s and to arrive in

5 See also: https://sci.esa.int/web/juice/-/61110-juice-instruments.

the Jovian system about six years later, at about the same time as Juice, in order to carry out some 40 near flybys of the satellite.

1.2.2. *The minor Jovian satellites*

Besides the Galilean satellites, Jupiter harbors a number of other satellites of small size. The primary ones are classified into three distinct families:

– the inner satellites (Metis, Adrastea, Amalthea, and Thebe), located inside the orbit of Io, with quasi-circular and equatorial orbits;

– four satellites located outside the orbit of Callisto, on orbits with high inclination and prograde movement, with a semi-major axis of 150 and 170 Jovian radii (Elara, Lysithea, Himalia, and Leda);

– four satellites that are even farther away, located on orbits with high inclination but retrograde movement, with a semi-major axis of more than 300 Jovian radii (Sinope, Pasiphae, Carme, and Ananke).

In the latter two cases, these are most likely asteroids captured by Jupiter, or fragments of larger parent bodies that broke up near Jupiter because of tidal forces.

In addition to these three families, a number of Jupiter's small satellites were discovered in the 2000s by ground-based observations.[6]

1.3. Saturn's satellites

Other than ground-based observations, our current understanding of the system of Saturn is based on observations made *in situ* by instruments on-board the four missions that conducted different phases of exploration: Pioneer 11 (1979), the first probe to fly over Titan and Saturn, Voyager 1 (1980) and Voyager 2 (1981), which provided a first look at the entire system of Saturn (see Figure 1.7), and finally Cassini-Huygens (2004–2017), which studied the system of Saturn as a whole, revealing the characteristics of the planet, its rings, and its satellites.[7]

6 For more, see the list at: https://solarsystem.nasa.gov/moons/jupiter-moons/overview/?page=0&per_page=40&order=name+asc&search=&placeholder=Enter+moon+name&condition_1=9%3Aparent_id&condition_2=moon%3Abody_type%3Ailike and the images at: https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA02530.

7 See also: https://solarsystem.nasa.gov/moons/saturn-moons/overview/.

In the Saturnan system, the Cassini orbiter has produced a wide range of new results about the 82 satellites known today, showing that these small bodies are far from being dead, icy, dull worlds, but rather active bodies with characteristics of resurfacing and cryovolcanism. Cassini's observations brought new surprises about several of these satellites. In particular, the combined research with the orbiter and the Huygens probe in the case of Titan, as well as the very close flybys of Enceladus, made it possible to reveal the satellites' distinctive characteristics and their potential in terms of exobiology (Coustenis and Encrenaz 2013; Coustenis and Raulin 2015; Schenk *et al.* 2018; Hand *et al.* 2020). Titan, with its thick atmosphere, in which we find methane clouds, and its surface covered with dunes, rivers, and lakes of liquid hydrocarbons, is a rich laboratory for studying chemical and physical processes similar to those on our planet, but with a different solvent and different substances. Furthermore, the measurements made by Cassini-Huygens indicated the very likely presence of a liquid ocean in the interior (Coustenis 2015). This is also the case for Enceladus: enormous plumes of icy particles that bear witness to geological activity and the discovery of simple organic compounds therein make it a privileged target for exobiology. Below, we will describe the major results from the Cassini-Huygens mission on Titan and Enceladus.

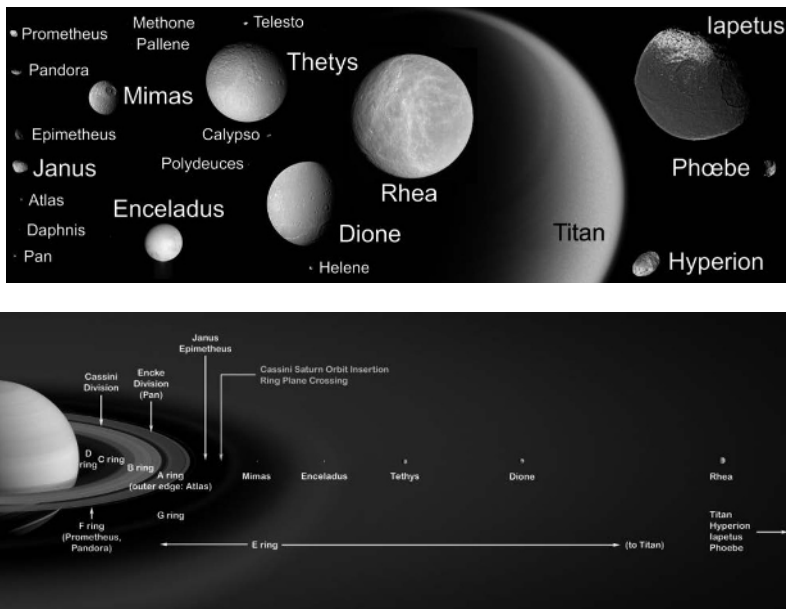


Figure 1.7. *A diagram of the lunar system of Saturn and its system of rings. Above, the various satellites at scale. Below, the rings and the main inner satellites (source: Wikimedia Commons, based on an image from NASA). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

1.3.1. *Titan*

Discovered in 1655 by Christiaan Huygens, Titan is the largest of Saturn's satellites and the second largest in the Solar System by size (5,150 km in diameter) after Ganymede ((Coustenis and Taylor 2008; Coustenis 2014); see also Figure 1.7 and Table 1.3, Volume 1). Titan, in synchronous rotation around Saturn (see Chapter 1, Volume 1, and Chapter 4 in this volume), moves along an orbit located 20 radii from the planet in about 16 days, which is also its period of rotation along its own axis. A recent study based on data from the Cassini probe shows that Titan is moving away from Saturn 100 times faster than previously supposed (11 cm per year). Before this rapid migration, 4.5 billion years ago, the satellite must have been much closer to the planet. This implies that the system of Saturn spread out much faster than we thought.

Titan's rotation period around the Sun is obviously the same as Saturn's: about 29.5 years. With an obliquity (angle between the axis of rotation and a line perpendicular to its orbital plane) of 27°, Titan, like Saturn, has seasons that each last a little longer than seven Earth years (Lorenz and Mitton 2008). Because of its almost synchronous rotation around Saturn, Titan's solid surface turns very slowly but, because of strong zonal winds, its atmosphere exhibits super-rotation. Titan's average distance from the Sun is 9.5 au. This corresponds to a solar flux above its atmosphere barely greater than 1% of the terrestrial flux. Moreover, Titan is sufficiently distant from the giant planet to avoid interaction with the rings. However, it is close enough to Saturn to allow its atmosphere to interact with the electrons in Saturn's magnetosphere. This interaction plays a key role, along with solar photons, in the chemical evolution of Titan.

Ground and space-based exploration of Titan has been providing basic information about the satellite for more than 350 years, particularly since the flybys by the Voyager 1 (1980) and Voyager 2 (1981) probes, which revealed that the surface of Titan is invisible to on-board cameras because it is enveloped by a thick atmospheric fog. Titan was found to be the only body in the Solar system other than the Earth to possess a dense atmosphere essentially made up of nitrogen (~98%), which combines with methane (~1.4% in the atmosphere) to give rise to a multitude of organic compounds such as hydrocarbons and nitriles (see Figure 1.8). Already at that time, this composition implied that Titan was a world that could resemble a primitive Earth, where prebiotic molecules might be found. This argument was one of the pillars on which the Cassini-Huygens mission was designed, which carried out the longest *in situ* exploration of a planet and its system of satellites to date (2004–2017).[8] Titan was at the heart of this exploration: 127 flybys were conducted,

8 See also: https://www.jpl.nasa.gov/missions/cassini-huygens/.

but it was especially the target for the European Huygens probe, which successfully descended into the atmosphere on January 14, 2005. All of the observations carried out by the instruments on the Cassini orbiter and the Huygens probe (Dougherty *et al.* 2010; Lorenz 2020) have allowed us to obtain a very detailed understanding of this far-off world.[9]

1.3.1.1. *The atmosphere of Titan: a biological factory*

Even before the Cassini-Huygens mission began, spectroscopic measurements of Titan's atmosphere from the ground but especially from the Voyager 1[10] mission had indicated the presence of a number of organic gases produced by photochemistry and photodissociation of dinitrogen, methane, and also oxygenated molecules ((Coustenis and Taylor 2008; Lorenz and Mitton 2008); see also Figure 1.8).

The Cassini-Huygens mission provided new information about the satellite's temperature and chemical composition (Dougherty *et al.* 2010; Coustenis 2014; Coustenis 2021).[11] The temperature and density profile measured by the HASI instrument on Huygens (see Figure 1.8) and by other instruments on Cassini showed a structured atmosphere that is the site of gravity waves above 400 km. We distinguish, in succession, the thermosphere (1,200–600 km), the mesosphere between 600 and 260 km, the stratosphere, where the temperature reaches its maximum of 187 K, while its minimum of 70 K is reached at the top of the troposphere at an altitude of 40 km, where a first temperature inversion occurs. The temperature on the surface of Titan is 93.6 K for a pressure of 1.5 bar (see Figure 1.8). The pressure and temperature values on the surface are therefore close to the triple point value of methane, which can therefore exist in gas, liquid, or solid state. In comparison, on the Earth's surface, environmental conditions are near the triple point of H_2O, so water cycles between the atmosphere and the surface, for example, through rain and dew evaporation (the hydrologic cycle). Titan is thus the only other place in the Solar System known to have a fluid cycle similar to that of water on Earth (Encrenaz and Coustenis 2017). However, on Titan, this happens with methane, and most of the methane resides in the atmosphere, while on Earth, most of the water is on the surface. The thermal profile changes depending on the region and the season (Horst 2017).

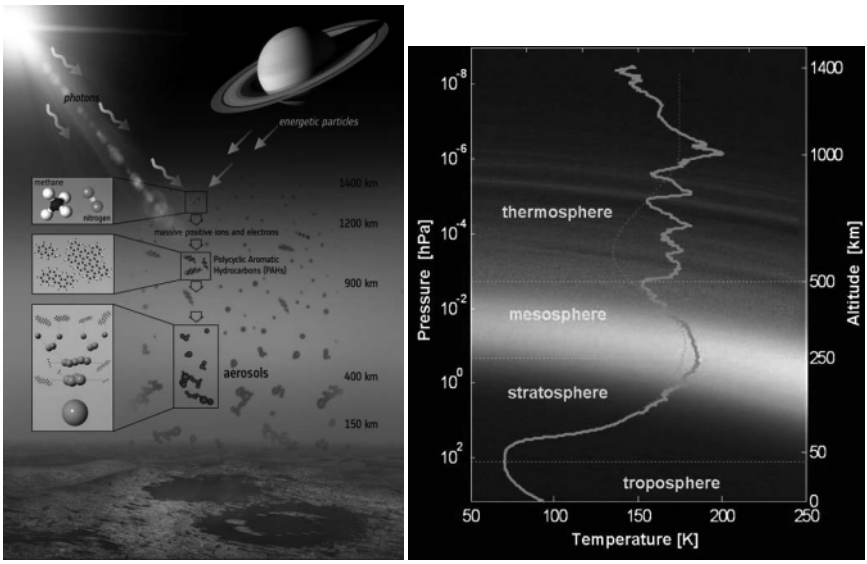
Cassini's ion and neutral mass spectrometer (INMS) described for the first time the ionic composition of the thermosphere where molecules are formed (see Figure 1.8). This data is complemented by measurements lower in the

9 Also see: https://www.esa.int/Science_Exploration/Space_Science/Cassini-Huygens/Cassini_instruments/.

10 See also: https://solarsystem.nasa.gov/missions/voyager-1/in-depth/.

11 See also: https://sci.esa.int/s/AM9ZGXA.

stratosphere acquired by the Cassini's Composite Infrared Spectrometer (CIRS) and detected by the Huygens's gas chromatograph mass spectrometer (GCMS) in the troposphere and during the descent toward Titan's equator on January 14, 2005. In the upper atmosphere, molecules of methane and nitrogen are dissociated by ultraviolet light from the Sun and by energetic particles accelerated by Saturn's magnetic field. The association of these parent molecules (N_2 and CH_4) produces a series of organic compounds (hydrocarbons like ethane, acetylene, and propane, and nitriles like hydrogen cyanide, acetonitrile, cyanoacetylene, etc.) which are present in small amounts (a few ppb (Coustenis 2021); see Figure 1.8). Some of these chemical components, such as hydrogen cyanide, HCN, are prebiotic molecules of interest. The atmosphere also contains small amounts of CO, CO_2, and H_2O of exogenous origin.



a) b)

Figure 1.8. *(a) The atmosphere of Titan; (b) the temperature profile measured by the HASI instrument during the descent of the Huygens probe through the satellite's atmospheric layers (source: ESA/ATG medialab; ESA/HASI). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

Complex refractory organic compounds combine and aggregate in the atmosphere, diffusing downward by creating aerosols and other condensates that form the clouds that hide the surface (see Figure 1.8). These clouds, made up primarily of methane, ethane, and other simple organic matter, form in the global fog and are dispersed and variable over long periods of time (Horst 2017). The

clouds produce rain that deposits organic particles on the surface, where they accumulate and eventually create the lakes that are currently observable in the north (see section 1.3.1.4). This may be one of the most convincing pieces of evidence in support of a "methane" cycle on Titan that mimics the water cycle on Earth (Encrenaz and Coustenis 2017; Coustenis *et al.* 2018).

1.3.1.2. *Evolution of Titan's atmosphere during the Cassini mission*

The chemical species in the atmosphere of Titan evolve over time as they are subjected to the effects of solar radiation and circulation (Coustenis and Encrenaz 2013; Horst 2017; Coustenis *et al.* 2021; Teanby *et al.* 2019). After 13 years of thorough exploration of the Saturnian system by the Cassini mission, we have had the opportunity to witness atmospheric changes through two seasons on Titan. The mission arrived at Saturn about two years after the northern winter solstice in 2004 and ended in September 2017, just after the northern summer solstice.

During the mission, Cassini was thus able to glimpse for the first time the transition from autumn to winter at Titan's south pole and to witness the arrival of summer in the north. Titan's spatial and ground-based observations through this period show important variations of temperature and chemical composition in the neutral atmosphere before and after the northern spring equinox (NSE) in mid-2009 provoked by the change in sunlight exposure.

The thermal field and the chemical contents of minor gaseous species and condensates in the stratosphere and the mesosphere of Titan were determined during the Cassini mission by applying radiative transfer analysis to the Cassini/CIRS spectra, which cover the far infrared range of 10 to 1,500 cm^{-1} and were recorded during Titan's flybys from 2004 to 2017. The results show relatively calm equatorial evolution ((Teanby *et al.* 2019, Coustenis 2021); see also Figure 1.9). Conversely, this is not the case at the highest elevations in the north and south: through the seasons, strong temperature changes are observed near the poles of Titan, accompanied by a decrease or an increase in radiative emitters.

Furthermore, seasonal effects play an important role in the circulation in the atmosphere. Hadley cells dominate the meridional circulation of terrestrial atmospheres, like the ones on Venus, Earth, Mars, and Titan, with a great variety in strength, amplitude, and seasonality (Encrenaz and Coustenis 2017). Simulations with zonal wind models based on wind speed data captured by Huygens suggested that Titan's atmosphere circulates in a single enormous Hadley cell. At the time of Huygens's descent, during Titan's summer, hot gas was rising in the southern hemisphere and downwelling in the northern hemisphere, swept along by a high-altitude gas flow from south to north and a low-altitude gas flow from north to

south. Such a large Hadley cell is only possible on a world in slow rotation such as Titan. The wind circulation cell from pole to pole seems to be centered in the stratosphere. Over the course of one Titan year (~30 Earth years), models predict that it should change every 12 years, with a transition period of three years (Coustenis 2021; Horst 2017; Teanby *et al.* 2019).

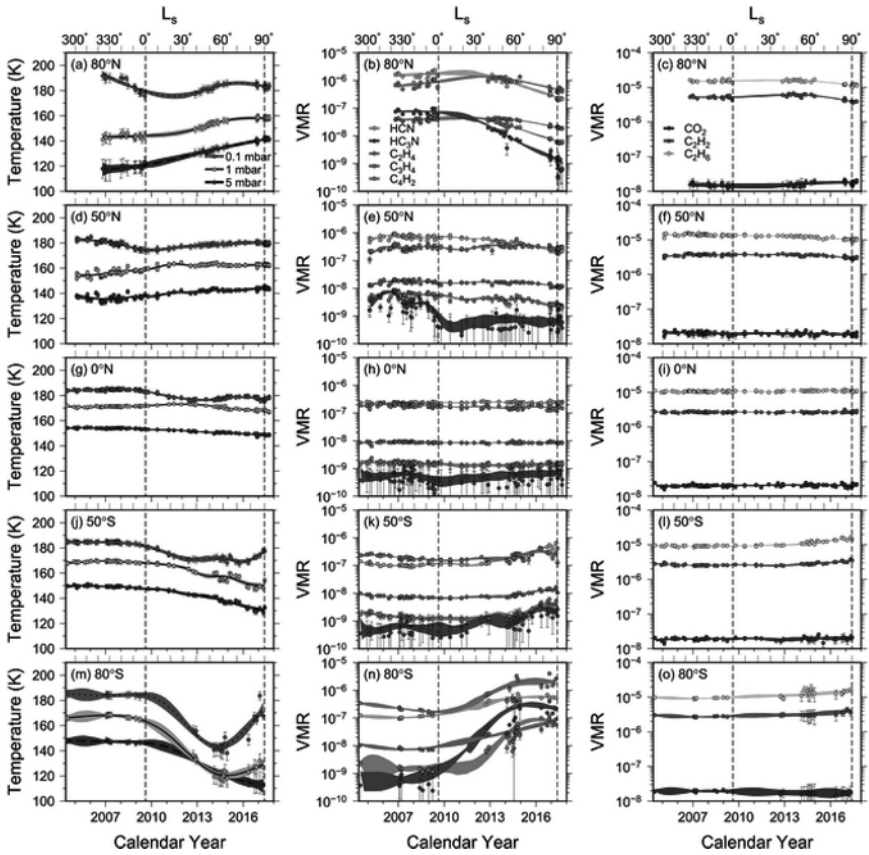


Figure 1.9. *Seasonal variations in the temperature and composition of Titan during the Cassini mission. (a) Change over time and latitude of the temperature at different levels of pressure; (b) and (c) change in the composition of the atmosphere for several gases (source: Teanby* et al. *2019)). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

During the first years of the Cassini mission, the northern latitudes exhibited an increased abundance until the NSE, which then decreased (from 2010 to 2012), returning to the values found during the V1 period, which took place one of Titan's years earlier in 1980, but remained still more elevated than at the south pole (see Figure 1.9). The increase observed in the north was associated with colder temperatures than in the south, between 15 and 29 K in the stratosphere at high latitudes. Things changed at the NSE, and until around 2014, with a strong drop in temperature observed near the south pole (adding up to a drop of about 40 K in four years after 2010), while a slight warming signaled the arrival of summer in the north after 2014 (about +6 K from February to September 2014, see Figure 1.9).

Furthermore, after the NSE, a large increase in several rare gases such as HC_3N and C_6H_6 began at Titan's south pole, while this was only previously observed at high northern latitudes, with an additional increasing trend for several other gases (C_4H_2, C_3H_4 and HCN). Confirmed over time (Coustenis 2021; see Figure 1.9), this trend indicates a seasonal atmospheric inversion on a large scale in Titan's unipolar circulation cell immediately after the equinox, with an increase in gases in the summer hemisphere and a corresponding decrease in the winter hemisphere.

As predicted by global climate models (GCM), a dynamic descending branch was observed for the first time at Titan's south pole, near the NSE, provoking reheating of the mesosphere (starting at around 400 km) via adiabatic heating and an increase in haze for latitudes above 80°S: indeed, it forced the air from the high atmosphere, where molecules form, to move toward the lower levels, leading to an enrichment in molecules at altitudes above 400 km, observed near the south pole in mid-2011 and later at even lower altitudes as the autumn progressed in the south. However, while the temperatures in the upper atmosphere should increase via adiabatic heating because of the expected strengthening of the vertical speed of the descending branch, it was instead radiative cooling that was observed in early 2012 in the stratosphere. This cooling (see Figure 1.9) is due to the decrease in solar flux during meridional autumn and to radiative cooling via highly enriched molecules at high altitude, which exceeds the adiabatic heating due to the descending branch. Net total cooling at high meridional latitudes causes the temperature to drop to values as low as 115 K in the low stratosphere, which leads to condensation of the gases at the poles at altitudes higher than those normally observed for other latitudes (Horst 2017).

Later on, after 2014, a significant and sudden increase in the temperature of the polar meridional stratosphere (from 10 to 50 K in the pressure range from 0.5 mbar to 0.05 mbar) was recorded with a change in the shape of the temperature profile. An inverse effect was expected in the north, but it was only observed with certainty after 2015 (Coustenis 2021). While the concentration of chemical products has

continued to decrease near the north pole since that time, their abundance finally also decreased at the south pole, but only after a delay of two to three years. Indeed, in the stratosphere over Titan's south pole, some molecules remained abundant until around 2016, before experiencing a sudden and significant drop in 2017. In 2017, during the winter, Titan's south pole was losing its strong chemical growth, while the north pole had also slowly continued its decrease in gaseous opacities that had not picked up (see Figure 1.9). This indicates an asymmetrical response to the seasons in Titan's stratosphere (Coustenis 2019; Teanby *et al.* 2019).

In addition to the gases, observations of the southern stratospheric region of Titan in the autumn, while stratospheric temperatures are the coldest since the beginning of the Cassini mission, made possible the detection of condensates which had not previously been found in the north, including some new compounds such as benzene ice (C_6H_6). Several other unidentified signatures were observed in the spectra probing the deep stratosphere in a similar way; they could be spectral signatures of ice, probably mixtures of nitrile ice.

Data from Cassini impose constraints on photochemical and circulation models, which must take into account the asymmetry found in the behavior of the poles and the general environmental response of Titan to seasonal and dynamical forcing.

1.3.1.3. *Change in the atmosphere during a year on Titan*

With the conclusion of the Cassini mission, we have an almost complete picture of the evolution of the neutral atmosphere over a year on Titan by combining measurements from the IRIS infrared spectrometer on V1 acquired during the flyby of November 1980, with the CIRS and other continuous recordings from Cassini and Huygens from 2004 to 2017. Moreover, we have sparse intermediate data from ground-based and spatial observations such as with ISO or HST (Coustenis *et al.* 2013).

The composition values extracted from all of this data help us to search for inter-annual stratospheric thermal and chemical variations and provide the opportunity to evaluate the relative role of different physical processes in the long-term evolution of this complex environment. In mid-2010, when the season was exactly the same as during the V1 flyby, spectral analysis from Cassini/CIRS only showed limited inter-annual variations (Coustenis *et al.* 2013). A return to the temperatures and stratospheric abundance of 1980 was generally reached from 50°N to 50°S, which indicates that solar radiation is the dominant source of energy at 10 au, as on Earth, as expected by the general circulation and photochemical models. The exception concerned the more complex hydrocarbons (such as C_4H_2 and C_3H_4) and some nitriles in the north, where they were enriched at that time (Coustenis

2021). These results tell us more about seasonal, photochemical, and circulation effects on Titan, but remain rare and imprecise for the two seasons not covered by Cassini (summer to winter in the north).

1.3.1.4. *The surface of Titan*

Despite some indications of an inhomogeneous surface on Titan with light and dark regions already available before 2004, it was only with Cassini-Huygens that we were able to characterize the satellite's complex soil ((Coustenis 2014; Lorenz 2020); see also Figure 1.10)). One of the most effective applications of the synergy between the Cassini orbiter and the Huygens probe is the cartography of Titan's surface. While Cassini provided detailed views of Titan's surface with its camera, its spectrometer, and its radar, Huygens, descending through the atmosphere, sent back extremely detailed images with resolutions between 10 meters and 10 km. The Huygens Atmospheric Structure Instrument (HASI) provided the conditions of pressure and temperature for Titan's surface (1.5 bar and 93.7 K, see Figure 1.8).

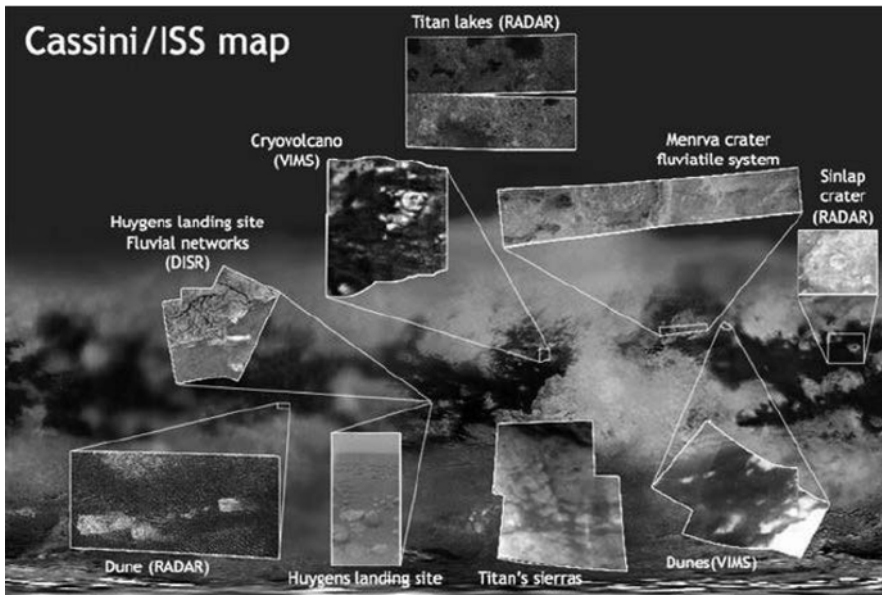


Figure 1.10. *The surface of Titan and some of the major discoveries made by the various instruments aboard the Cassini-Huygens mission: transitory atmospheric phenomena (clouds) and several geomorphological characteristics (craters, dunes, cryovolcanoes, channels, mountains, and lakes) are presented in this composite image (source: Université de Nantes and LESIA/SIGAL). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

Images of the surface of Titan taken by Cassini-Huygens show reliefs that resemble terrestrial landscapes, such as hills, dunes, and lakes ((Dougherty *et al.* 2010); see also Figure 1.10). But the components are completely different: a mixture of ice and organic substances. The ambient conditions and the direct measurement of the methane that evaporated under the probe after landing imply that the active erosive agent is liquid methane. The diversity of terrains on Titan observed by the Cassini-Huygens instruments is associated with multiple geological processes.

The erosion and deposit of solid and liquid matter by wind and rain shaped the surface of Titan. The liquids evaporate, forming clouds from which re-liquefied gases fall in the form of rain, which sculpts the surface of the satellite with rivers, seas, and lakes (depending on their size). In 2007, Cassini's radar discovered hydrocarbon lakes near Titan's north pole. The area covered by these structures ranges from less than 10 km^2 to more than 100,000 km^2. They are essentially confined to the region above latitude 55°N, but other small lakes have been discovered further south, such as Ontario Lacus. To date, several hundred areas of liquid water have been identified and mapped, and about 30 of them have been named. Lakes often form in depressions that are 600 to 800 meters deep. The three largest seas on Titan, Ligeia, Punga, and Kraken, extend over hundreds of kilometers and have shredded banks (see Figure 1.10) such as those observed on Earth in regions where reliefs have been filled by liquid (such as lakes in Alpine valleys). Cassini's radar measurements supplied bathymetric profiles that indicate depths of 100 to 200 meters for liquid methane lakes in the north. On the other hand, Lake Ontario, one of the only ones observed in the southern hemisphere, is primarily composed of ethane (Dougherty *et al.* 2010; Coustenis 2014). These lakes are found around 100 m above seas, and are similar to terrestrial karstic lakes, which implies the existence of subterranean rivers. The hydrological difference between the north pole regions indicates processes of formation that are probably different: it has been suggested that some lakes formed after explosions of heated nitrogen that created high barriers. Depressions at the south pole could be vestiges of ancient seas. This asymmetry between the two poles may be the result of long-term variations in climate (Coustenis *et al.* 2018; Lorenz 2020).

Radar observations suggest that the final fate of this precipitation is the production of dunes covered with organic matter, which were observed around Titan's equator by Cassini's radar. These dunes are the same size and form as terrestrial linear dunes, like those in the Namibian and Sahara deserts. This type of dune is formed by variable winds, which on Titan can be generated by atmospheric tides due to Saturn whose distance to Titan is variable, since its orbit is relatively eccentric. A vast sea of sand covers most of Titan's surface: elsewhere, we can see a deeply eroded terrain, at an altitude below that of the neighboring regions, called

Xanadu, which does not contain dunes. Xanadu seems to be one of the oldest regions on Titan: we find degraded circular structures there, which may be eroded vestiges of impact craters ((Coustenis 2015); see also Figure 1.10).

Drainage channels and dendritic networks observed by the Cassini radar, which are probably trenches like those at the Huygens landing site, have been observed at low and medium latitudes, although canyons of several hundreds of meters exist elsewhere. At high latitudes, we see meanders that suggest a deposit of small-grain sediments. The fluvial modification of the surface is obvious at the Huygens landing site, confirmed in Cassini's radar and near infrared images at much larger scales (Coustenis 2014; Lorenz 2020).

The almost complete absence of impact craters indicates that the surface is continually modified by active geologic processes such as æolian deposits (winds) and fluvial erosion (streams and rivers), which may affect a larger scale tectonic activity like the one, in some places, that formed mountain chains more than 1 kilometer high. Several zones may be active on the surface of Titan: domes, potential cryovolcanic flows and bright spots, mountain chains. The temperature on Titan is so low that water ice plays the role of rocky substrate, and water plays the role of lava. Although proof of active volcanism is not yet completely forthcoming, there are apparent changes on the surface that strongly suggest it. The region called Sotra Patera, for example, shows traces of possible cryovolcanic activity with flows of liquid water. Furthermore, the detection of argon 40 suggests that Titan's interior is geologically active. Theoretical calculations suggest a heat flow of about 8% of Earth's, which is enough to initiate cryovolcanism.

Cassini-Huygens thus found that the geological processes – impact, tectonic, fluvial, æolian – are similar to those on Earth, more so than those on Venus or Mars (Lorenz and Mitton 2008; Coustenis 2014; Encrenaz and Coustenis 2017). Titan could well be the best analog of an active telluric planet, although with different surface materials (Coustenis and Raulin 2015; Lorenz 2020).

1.3.1.5. *The interior of Titan*

The global density of Titan (1.88 g cm^{-3}) indicates that rocks and ice exist in equal proportions and that the body is differentiated into several layers. Titan may have an icy crust that is 50 to 150 km thick, above a liquid salt ocean that is a few hundred kilometers deep, with 10% to 30% dissolved ammonia acting as antifreeze. Below we find an ice layer under high pressure, followed by several layers of different forms of crystalline water ice mixed with ammonia ice and hydrocarbon ice. At the center is a rocky core that is more than 3,000 km in diameter (Dougherty *et al.* 2010; Coustenis and Raulin 2015).

Measurements by Cassini of a variation, small but significant, in Titan's rotation period have been interpreted to be the result of decoupling of the crust and the deep interior, separated by a liquid layer. In support of this argument, some of the surface features shifted by up to 30 km between October 2005 and May 2007, which suggests that the satellite's crust is mobile. An additional indication of the existence of such an ocean was discovered by the Huygens probe, which detected very low frequency radio waves in Titan's atmosphere; this is a Schumann resonance between the surface and the ionosphere, which implies the presence of a highly conductive surface under the successive layers of ice. Indeed, we think that the satellite's surface is a poor reflector of this type of wave, and that therefore they are reflected instead by the liquid-ice transition of an internal ocean.

Furthermore, measurements of variations in Titan's rotation and the amplitude of tides on its surface by Cassini in 2012 showed that the icy crust deforms in step with the orbital period, which is in agreement with the presence of a global ocean within a few hundred kilometers of the crust, as suggested by Huygens's measurements.

1.3.1.6. *Origin of the atmosphere and interactions with the surface and the interior*

Cassini-Huygens also provided important information about the origin and evolution of Titan's atmosphere by measuring the concentrations of rare gases (such as argon, observed for the first time) and their isotopic abundances, as well as that of nitrogen and the ratios of the stable isotopes of carbon. These measurements provide important indications about the global role of atmospheric escape, chemical conversion, outgassing, and recycling in the evolution of Titan's atmosphere (Catling and Kasting 2017; Schenk *et al.* 2018).

As we saw above, Titan's atmosphere and its surface are tightly linked. The organic matter falling from the atmosphere collects on the surface (see Figure 1.8) where it contributes to the formation of the observed geological forms. Analysis of Cassini's near-infrared spectro-imaging and radar data looking at the terrains at low and medium latitudes shows significant variations with time of the albedo and the composition of different areas. In this latitudinal dependence of the composition of Titan's surface, water ice seems to be the primary constituent at latitudes above 30°N and 30°S, while Titan's equatorial region is dominated in part by a very dark unknown substance and by another substance that has the properties of tholins deposited through the atmosphere (see Figure 1.8). The similarities and differences of the albedo between the different geomorphological units may indicate cryovolcanism (volcanoes of ice that spew water and other volatile products in the liquid or vapor phases on the surfaces of the giant planets' icy satellites), which thereby add methane into Titan's atmosphere and explain its reconstitution.

Indeed, the persistent presence of methane in Titan's atmosphere is a mystery because the Sun's ultraviolet radiation is capable of dissociating CH_4 molecules, and, therefore, since the satellite's formation 4.5 billion years ago, primary methane should have been completely destroyed. As a result, the presence of a source re-injecting it into the atmosphere must exist. In addition to cryovolcanism, other theories have been proposed: the sublimation of layers of frozen hydrocarbons, or the presence of oceans or large lakes of liquid methane on Titan's surface. It should be noted that the mass of carbon contained in the methane and its by-products in Titan's atmosphere, seas, and dunes exceeds by more than an order of magnitude that of the carbon present on Earth in the ocean, the biosphere, and fossil fuels (Dougherty *et al.* 2018).

The origin of Titan's atmosphere as a whole has been a source of debate since its discovery. According to the main theory, cometary impacts would have brought ammonia ice to Titan, and the ammonia would then have decomposed into the nitrogen that we see today. However, recent data about the comet 67P/Churyumov-Gerasimenko from the Rosetta mission and the constraints brought by isotopic ratios and rare gases reveal that a wealth of complex cometary organic material including nitrogen has been brought to Titan's interior. The measurements of the $^{36}Ar/N$ ratio by Cassini-Huygens as well as recent theories indicate that Titan's hot interior is responsible for the outgassing of N and other organic matter from the outer core within 300 km of the ice-rock interface, forming around 50% of today's atmosphere (Coustenis 2021). Subsequent measurements and internal heating models should allow us to better understand the nature and extent of cryovolcanism on Titan and the origin of its atmosphere.

1.3.2. *Enceladus*

Enceladus is one of Saturn's smaller satellites, with a diameter of 500 km (see Table 1.3, Volume 1). Enceladus is in 2:1 orbital resonance with Dione, which generates tidal forces. The energy produced by this process heats the interior and may govern its geological activity. Enceladus has one of the highest albedos of any object in the Solar system (Schenk *et al.* 2018). Covered with water ice, it reflects almost 80% of the Sun's light that it receives, which explains its extremely low surface temperature (around 73 K).

Enceladus presents five different types of terrain. Some parts are covered with craters whose diameter can be as large as 35 km, while other zones are devoid, which implies resurfacing events in a very recent geological past. There are fissures, plains, undulating terrains, and geysers. The region of Enceladus's south pole, in particular, is sprinkled with blocks of ice that can be as much as ten meters high, and

the surface is sculpted by tectonic forms that are specific to the region: deep crevasses and fissures where the temperature is dozens of degrees higher than on the rest of the surface, indicating that below the icy crust, there may be liquid water (see section 5.3.3).

When Cassini performed its first encounter with Enceladus on February 17, 2005, the magnetometer saw that something was affecting Saturn's magnetosphere, with its plasma slowing and deviating in the vicinity of Enceladus. The data collected during the March 9, 2005 flyby provided additional evidence of the existence of an atmosphere around Enceladus's south pole. The cosmic dust analyzer recorded thousands of impacts from minuscule particles of dust and ice coming from a cloud around the satellite or from the adjacent Saturn's E ring. Indeed, several mathematical models show that this ring is unstable, with a lifetime between 10,000 and 1,000,000 years. Consequently, the particles that make it up must be constantly replenished. Enceladus is in orbit inside this ring, in its most narrow and dense area (see Figure 1.7), which has led us to suspect since the 1980s that Enceladus is the primary source of the E ring's particles. This hypothesis was confirmed during Cassini's close flybys in 2005 (Schenk *et al.* 2018).

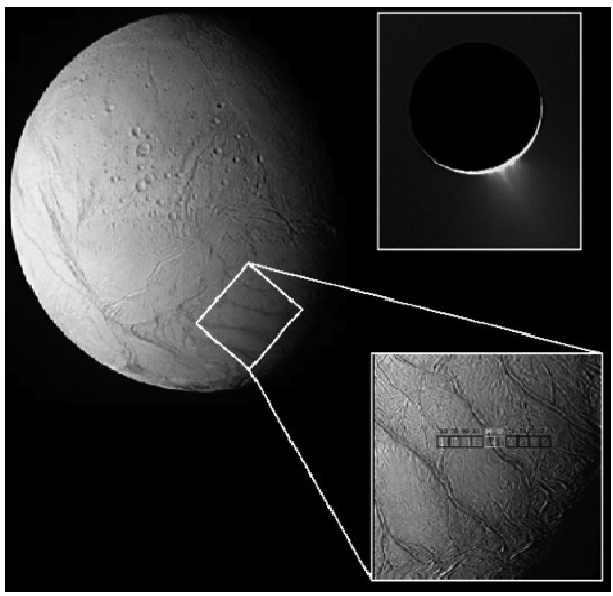


Figure 1.11. *The surface of Enceladus seen by Cassini, with the "tiger stripes" in the south, from which emanate plumes of water vapor (lower right zoom) (source: NASA). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

Cassini also provided definitive proof that Enceladus is geologically active, when several of Cassini's instruments detected plumes of gas and ice particles emanating from a series of hot fractures centered on the south pole, nicknamed the "tiger stripes" ((Schenk *et al.* 2018); see also Figures 1.11, 5.10, and 5.11). Moreover, the density measured by Cassini is 1.6 10^3 kg/m^3, higher than Saturn's other satellites, suggesting an internal composition that is richer in silicates and iron. The largest abundance of heavy elements may explain a higher degree of heating by radioactive elements than on the other satellites.

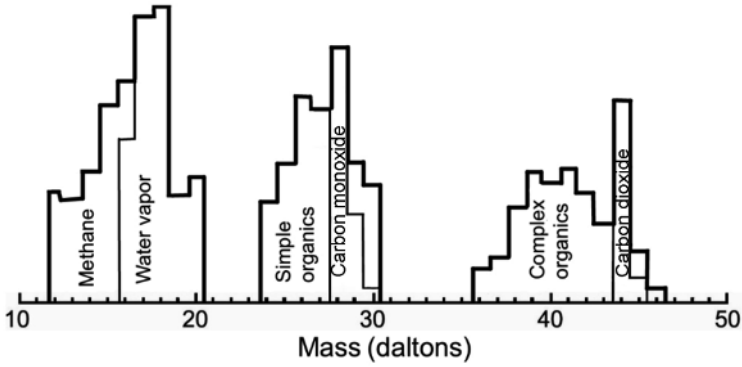
Several pieces of data from Cassini showed that reservoirs of liquid water under Enceladus's surface have produced geysers. In March 2008, Cassini swept Enceladus's south pole at an altitude of 52 km and dove into one of the plumes, collecting particles and gas and determining their composition. The gas analyzed by the INMS instrument closely resembled gases emitted by comets, showing the presence – in addition to water – of CO_2, methane, and other organic species (see Figure 1.12). The CIRS instrument on Cassini established that Enceladus's south pole was the hottest part of the satellite, surprisingly hotter than the equator. During its most recent flybys, Cassini detected complex molecules in the plumes, with atomic masses greater than 200 AMU. Like Titan, Enceladus therefore seems to be an organic chemical factory.

Enceladus is also the second icy satellite known to exhibit cryovolcanism. The other is Triton, but its cryovolcanism is not *a priori* connected to an internal source of heat. Enceladus can therefore be used to study the active processes that formed the surfaces of the other icy satellites. These processes include tidal heating, cryovolcanism, and ice tectonics (Hand *et al.* 2020).

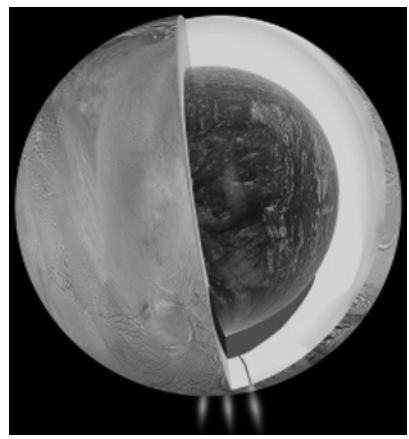
Enceladus ejects plumes of salty water intermingled with grains of sand rich in silica, nitrogen (in the ammonia), nutrients, and organic molecules. The spectra also include traces of simple hydrocarbons such as methane (CH_4), propane (C_3H_8), and acetylene (C_2H_2) as well as formaldehyde (CH_2O), which are carbon compounds (see Figure 1.12). In particular, the presence of silica nanoparticles in Enceladus's plumes confirms that the liquid layer is in contact with a porous, rocky core: the water temperature to form these particles must be very high (360 K), suggesting that Enceladus possesses hydrothermal springs on its seabed.

In terrestrial oceans, hydrothermal sources host burgeoning life despite the extreme environment (Coustenis and Encrenaz 2013; Schenk *et al.* 2018; Hand *et al.* 2020). While other satellites in the Solar System have oceans of liquid water covered by kilometers of icy crust (Ganymede, for example), in the case of Enceladus, as on Jupiter's satellite Europa, pockets of liquid water may be only a

few dozen meters under the surface (see Figure 1.12b). Enceladus is undoubtedly one of the places in the Solar System where exploration is most likely to find a habitable environment.



a)



b)

Figure 1.12. *(a) Mass spectrum of a plume on Enceladus and (b) a model of its interior (source: NASA/SWRI). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

1.3.3. *The other icy satellites*

This category includes Saturn's satellites other than Titan and Enceladus, whose main properties we will present (from outer to inner, Phoebe, Iapetus, Hyperion, Rhea, Dione, Tethys, and Mimas, Figure 1.7). All of these satellites, except for

Phoebe and Hyperion (which are probably captured objects), are locked by Saturn's tides in a 1:1 spin-orbit resonance, and they therefore always show the same side toward the planet. The recent discoveries by Cassini showed that these worlds are active, with the possible presence of liquid oceans as well under Dione and Mimas, and they interact strongly with the rings (Schenk 2010).[12] Furthermore, Cassini also discovered the presence of organic compounds (primarily hydrocarbons) on several of Saturn's satellites, including Iapetus, Phoebe, and Dione, thanks to their signatures in the spectro-imaging data collected by Cassini, showing that the dark substance in Saturn's system could be of organic origin.

1.3.3.1. *Regular and irregular satellites*

We say that several celestial objects constitute a "dynamic group" when the parameters that define their orbits are similar (Schenk 2010; Lang 2011). Saturn's most distant satellites belong to three dynamic groups:

– the Norse group;

– the Inuit group;

– the Celtic group.

The Norse group is composed of 29 outer satellites whose distances from Saturn range between 12 and 24 million km, with orbital inclinations between 135° and 175° and eccentricities between 0.13 and 0.7. All of these satellites have retrograde orbits, which indicates that they are objects captured by Saturn that came from the Centaur region or from beyond Neptune. Because of its orbital characteristics, Phoebe is part of the Norse group and may be the largest fragment resulting from the collision that created the group. The Inuit group is composed of five satellites whose distances from Saturn range between 11 and 18 million km, with orbital inclinations between 40° and 50° and eccentricities between 0.12 and 0.48. The Celtic group is composed of four outer satellites that share very similar orbital parameters: a distance from Saturn between 15 and 18 million km, orbital inclinations between 35° and 40°, and eccentricities between 0.45 and 0.53.

Closer to Saturn, we find *Rhea,* its second largest satellite, with a mean radius of 764 km. Rhea orbits the planet in 4.5 Earth days and is extensively cratered, much more so than Tethys and Dione, which are inner satellites. Rhea is the only satellite in the Solar System around which a disk of debris and a ring have been observed. Surface temperatures range from 99 K in sunny areas, dropping to 53 K in unlit areas. Rhea has a high albedo, showing that most of its surface is made up of water

12 See also: https://en.wikipedia.org/wiki/Moons_of_Saturn#/media/ File:Saturnmoonsdiagram.

ice, which, at Rhea's temperatures, acts like a rocky substrate. Rhea's density (1,233 kg/m^3) suggests that the satellite's interior is composed of three-quarters ice and one-quarter rock, with a homogeneous mixture of these two components, as indicated by its moment of inertia, which is larger than it would be if Rhea had a rocky core. A thin exosphere of oxygen and carbon dioxide has been detected around Rhea: during its diurnal rotation, Saturn's magnetic field periodically sweeps the satellite's surface, and the energy particles trapped in its lines interact with the surface by dissociating those organic molecules that are present and releasing oxygen and carbon dioxide. Its distance is 527,000 km from Saturn, such that the planetary tides do not lead to sufficient internal heating to produce flows of liquid water on the surface, which would have the effect of renewing it by wiping away pre-existing craters. However, the existence of regions with craters of different sizes indicates that a significant event renewed the surface in Rhea's distant past, given that there is no trace of young craters and that the average age of the plains is estimated to be about four billion years. The images obtained by the Cassini orbiter show deep canyons whose walls expose water ice. These cliffs also seem to bear witness to the existence of past tectonic activity.

Phoebe is one of the largest irregular satellites in the Norse group, as well as being the most distant of Saturn's satellites. Recently, thanks to infrared observations from the Spitzer satellite, a ring/disk around Saturn with very low density but extremely large (6 million km in diameter) was discovered, and its outer edge touches Phoebe's orbit: this is the E ring. Phoebe is therefore, with Enceladus and possibly Thetis and Dione, at the origin of this ring, which is supplied with dust ejected during meteor impacts. Contrary to most large satellites orbiting Saturn, Phoebe has a very dark albedo (0.06). Its surface is cratered and there is water ice on the wall of one of the largest craters. Its weak albedo and its retrograde orbit suggest that Phoebe came from the outer Solar system, a region where there is a lot of dark material, and that it was captured by Saturn. The hypothesis has been put forth that Phoebe could be a captured Centaur; in other words, an object from the Kuiper belt that migrated to the inner Solar System, providing planetologists with the opportunity to study a primitive object.

Iapetus, which was discovered in 1671 by Jean-Dominique Cassini, is the only regular satellite not to orbit in Saturn's equatorial plane (orbital inclination of 7.6°). It is in a 3:1 orbital resonance with Titan. Its main characteristic is the strong asymmetry of its two hemispheres: one is dark as coal (albedo 0.03–0.05) and the other is very bright (albedo 0.5–0.6). Several scenarios have been proposed to explain this asymmetry: dark particles from faraway Phoebe sweeping Iapetus; cryovolcanism, with eruptions of hydrocarbons that could form the dark surfaces after solar radiation has provoked chemical reactions in the ejected matter; the effect

of thermal segregation due to the accumulation of dark matter on the hot side while volatiles migrate toward the cold side, which the ice makes even brighter. It is possible that in the distant past Iapetus was subjected to a small influx of dark matter from an external source (Phoebe, for example), which initiated this process. Another striking characteristic of Iapetus is an equatorial ridge, a mountain chain that is more than 10 km high, encircling the satellite's equator. On the side that never faces Saturn, the ridge seems to be broken, and even brighter isolated mountains have been observed there. There are two theories about the formation of this ridge: according to some, the ridge accumulated at a time when Iapetus had a much faster rotation than today; others think the mountain range is the result of material from the collapse of a ring.

Hyperion has a very eccentric orbit ($e = 0.10$) and is in 3:4 orbital resonance with Titan, which results in a rather chaotic 21-day orbit. Hyperion's density is a little more half that of water, which is probably due to a composition dominated by water ice and lighter substances, such as carbon dioxide or methane, with a porosity of more than 40%. This description is compatible with the hypothesis of a "catastrophic" origin for Hyperion, which would have been the result of the accretion of small icy and rocky bodies from the destruction of a primordial satellite by a major impact. The *rubble pile* thus formed has never attained sufficient mass to compact. Hyperion's surface is riddled with particularly deep craters that show no signs of ejecta, but whose interior shows signs of sliding terrain and wall collapse. The satellite's high porosity and low density suggests that these craters were formed by compression rather than excavation and that the ejected material tended to leave the satellite immediately. Many craters on Hyperion are bright, a sign of the presence of water ice, but the floors of the oldest of these craters have a lower albedo and a redder color as a result of an accumulation of dark matter left over from the sublimation of volatiles by heating due to extended daytime exposure to solar radiation.

Dione is a medium-sized icy satellite (1,124 km in diameter) in orbit around Saturn with a period of 2.7 days and a distance of 377,400 km. Dione has gravitationally locked two small satellites in its orbit around Saturn, called, by analogy with Jupiter's Trojan asteroids, the "Trojans" of Dione: *Helene* and *Polydeuces*. Dione is in orbital resonance with Mimas and Enceladus. Its density is 1,480 kg/m^3, implying that about a third of the satellite is composed of a dense core (probably silicates), with the rest being water ice. A very fine ice powder coming from Saturn's E ring, itself supplied by Enceladus's geysers, constantly bombards Dione's surface, where the average temperature is 87 K. The main geological characteristics of Dione's surface are heavily cratered terrains, with craters of up to 100 km in diameter, plains with a moderate or low number of craters, and fractured

areas. The heavily cratered areas are, for the most part, on the trailing hemisphere. Logically, the leading hemisphere should be the one most frequently hit by impacts, but it seems that Dione was recently subjected to one or more impacts that turned it by 180°, which inverted the roles of the hemispheres. The fractured areas are dominated by very long subsidence fractures, similar to those observed on Rhea.

Tethys is composed almost entirely of water ice, making it very bright: its average albedo is 0.8. It looks a lot like Dione and Rhea except that it is less cratered, because its proximity to Saturn results in strong tidal heating effects that keep the layer of ice under the surface partially molten, allowing for effusions of liquid water that have erased or smoothed pre-existing surface structures. However, two giant structures persist on Tethys's surface: an immense impact crater and a very long valley. The Odysseus crater (400 km in diameter) dominates the satellite's western hemisphere, while the Ithaca Chasma is a valley (2,000 km long and 100 km wide, with a depth of between 2 and 3 km) that circles Tethys from north to south pole, at Odysseus's antipodes. Two hypotheses have been proposed to explain the origin of this valley by surface fracturing:

a) ice expansion, a consequence of the solidification of internal liquid water;

b) the impact that created Odysseus, generating seismic waves that interacted destructively at the crater's antipodes.

At the L4 and L5 Lagrange points of its orbit, Tethys harbors two small "Trojans" that are gravitationally locked in its own system − *Telesto* and *Calypso*.

Mimas is the smallest and closest of Saturn's icy satellites. Its low density suggests that it is composed essentially of water ice, the only substance that has been detected on its surface. In addition to its spin-orbit resonance with Saturn, Mimas is linked by its orbital resonances with Tethys (2:1), Dione (3:1), and Enceladus (3:2). Mimas interacts with particles from Saturn's B ring, with which it is in 1:2 resonance, creating divisions in the B ring and density waves in the A ring. Most of Mimas's surface is saturated with craters that are 40 km in diameter, but at the south pole the craters are generally smaller (20 km in diameter or less). This suggests that episodes of fusion of the icy crust or other processes that have renewed the surface occurred later than on the rest of the satellite. Mimas's distinctive characteristic is the giant Herschel crater (130 km in diameter), which covers a third of the surface, with walls that are around 5 km high and a central peak that is 6 km high. The shock waves generated by the impact probably caused the fractures, called *chasmata*, which are seen on the side of Mimas, located at Herschel's antipodes. The presence of such a heavily cratered surface, without any melting, implies that Mimas's interior is made up of solid ice. This is a paradox: being so close to Saturn and

having a much more eccentric orbit than Enceladus's, Mimas should show stronger tidal effects and even more activity. Another surprise came from observations of Mimas in February 2010, which showed large differences of temperature on the surface that could not be explained by differences in the visible albedo. Mimas causes major disturbances in the orbits of the smaller satellites – *Methone* (D = 3 km), *Pallene* (D = 4 km), and *Anthe* (D = 2 km) – that orbit between Mimas and Saturn; they form the group called the *Alkyonides*.

1.3.3.2. *The small satellites near the rings and their interactions*

We have seen that Enceladus and Mimas have very significant interactions with the rings. The gases and microscopic particles emitted by geysers on Enceladus's meridional hemisphere constantly supply the E ring. Orbital resonances between Mimas and the rings of Saturn are responsible for the Huygens division, which delimits the B ring from the Cassini division, as well as several density waves in the A ring.

At 151,000 km from Saturn, *Janus* and *Epimetheus* are found between the weak F and G rings located between the A ring and the E ring (see Figure 1.7) and share the same orbit, which they travel in 17 hours. These satellites are both shaped like a large potato, with dimensions of $196 \times 192 \times 150$ km for Janus and $135 \times 108 \times 105$ km for Epimetheus; their low density (700 kg/m^3) seems to indicate that they are made up of a group of fragments held together by gravity. Their surface is cratered, with several craters larger than 30 km, and show grooves similar to those that characterize the surface of Phobos, one of Mars's two satellites. All of these elements seem to indicate that the fragmentation of a single satellite, shortly after the birth of the system of Saturn, led to the formation of this pair of satellites.

Six other small satellites have more limited contact with the rings; they are referred to as *ring shepherds* because their gravity sculpts one or more edges of the ring to which they are closest or in which they are immersed, sending grains and dust backward, which tends to escape. *Pan*, which is the innermost of Saturn's known satellites, has a mean radius of 14.1 km. It orbits at 134,000 km from Saturn in 13.8 hours, within the A ring where it formed and where it keeps the 325 km-wide Encke gap empty. *Daphnis* has a mean radius of almost 4 km and completes its orbit in 14 hours, at 136,500 km from Saturn, which creates the Keeler gap. *Atlas* orbits around the exterior edge of Saturn's A ring, which it maintains empty. Like Pan, Atlas's shape is characterized by a significant equatorial crest. It has a mean radius of 15.1 km and orbits at 137,670 km from the planet, completing a revolution in 14.4 hours.

Pandora and *Prometheus* work together to hold the F ring's particles and fragments in place. They orbit at about 140,000 km from Saturn and complete their revolution in about 15 hours. Pandora has a mean radius of 40.7 km and is covered by a layer of fine water ice powder. Prometheus has a mean radius of 43.1 km and a lower density than the other icy satellites, which implies a high degree of porosity. Its surface is less cratered than Pandora, Janus, or Epimetheus.

Aegaeon is Saturn's smallest known satellite to date (0.12 km in mean radius). It orbits Saturn at a distance of 167,500 km and completes its almost perfectly circular orbit in 19.4 hours. *Aegaeon* is immersed in the G ring, which was formed by debris ejected following impacts to the satellite that first produced an arc, which then spread to form the rest of the ring.

1.3.4. *Challenges for future missions in the Saturn system and Dragonfly*

Each of Saturn's satellites is distinctive. The largest have complex geological histories controlled by the heating and cooling of their interiors. But the small satellites also have unique geological histories because of their different positions in relation to Saturn, their relations with the ring system, and their interaction with the planet's magnetic field. The opportunity to observe, with Cassini, the ring-satellite interactions over a long period allowed us to understand the many evolutionary processes of material in orbit in the Saturn system: accumulation, fragmentation, renewal, aging, and capture. Their similarities and differences, which are the foundation of the Saturn system's uniqueness, show us the paths to follow to better understand the origin and overall evolution of the planetary system and invite future exploration.

The Cassini-Huygens mission discovered specifically that Titan and Enceladus possess active organic chemistries with seasonal variations, unique geological characteristics, and possibly internal liquid water oceans. It will be interesting to further explore all of these worlds now that the Cassini mission has ended in a spectacular *Grand Finale* on September 15, 2017 when it plunged into the atmosphere of Saturn. The final data collected at that time is still being analyzed, but in any case there will be many questions left to answer. For example, Saturn's deep atmosphere, Enceladus's plumes, and the two major themes of the exploration of Titan – the methane cycle as an analog of the terrestrial water cycle and the chemical transformations of complex organic molecules in the atmosphere and on the surface – justify another exploration of the Saturnian system.

Several ideas for new missions have been proposed to space agencies, and some have been or are in the process of being studied, for example, a probe to the interior of Saturn, similar to what Galileo was for Jupiter, but also orbiters, landers in the lakes, gliders, balloons, and drones dedicated to Titan or Enceladus.

In particular, *Dragonfly* is a NASA mission that will consist of sending a mobile robotic lander to Titan in order to study, among other things, the prebiotic chemistry and extraterrestrial habitability at several locations, where it will conduct vertical takeoffs and landings.[13] The mission will take advantage of the presence of a dense atmosphere and relatively low gravity: it will consist of a rotorcraft weighing about 450 kg, which will carry out multiple short flights to study the low atmosphere and the surface of Titan, using an electric battery as its energy source. This will be recharged on the ground by a radioisotope thermoelectric generator. When on the ground, it will study the composition of organic matter and ice on the surface by using a mass spectrometer and an active neutron gamma ray spectrometer. The drone will also carry instruments for meteorological and seismic studies. Dragonfly is expected to launch in 2027 and land on Titan in 2035 near the equator during the same season and at the same latitude as Huygens in 2005, although 30 years later, which is equivalent to one year on Titan.

While waiting for such an *in situ* exploration in the mid-2030s, ground-based measurements will be essential to continue exploring the satellites of Saturn.

1.4. The satellites of Uranus and Neptune

The Voyager 2 spacecraft explored the systems of Uranus and Neptune in the 1980s. Voyager 2 flew over the planet Uranus, which is characterized by a rotational axis that is almost parallel to its orbital plane, on January 24, 1986. This mission discovered a total of ten new natural satellites orbiting Uranus and studied its atmosphere and its ring system. Voyager 2 is also the only spacecraft to have flown over Neptune, on August 25, 1989, at 4,950 km from the planet's north pole and 39,790 km from Triton. As no other mission has explored these outermost planets in our Solar System to date, our knowledge of these icy giants remains limited.

1.4.1. *The satellites of Uranus*

Among the 27 known satellites of Uranus, *Oberon* and *Titania* are the largest and were the first to be discovered, by William Herschel in 1787. William Lassell

13 See also: https://dragonfly.jhuapl.edu/.

discovered the next two, *Ariel* and *Umbriel*, and Gerard Kuiper (1905–1973) discovered Miranda in 1948 (see Figure 1.13). In 1986, Voyager 2 discovered 10 additional satellites, which are only 26 to 154 km in diameter: *Juliet*, *Puck*, *Cordelia*, *Ophelia*, *Bianca*, *Desdemona*, *Portia*, *Rosalind*, *Cressida*, and *Belinda*. Since then, astronomers using the HST and ground-based telescopes have increased the total number to 27 satellites, which are for the most part tiny and dark.

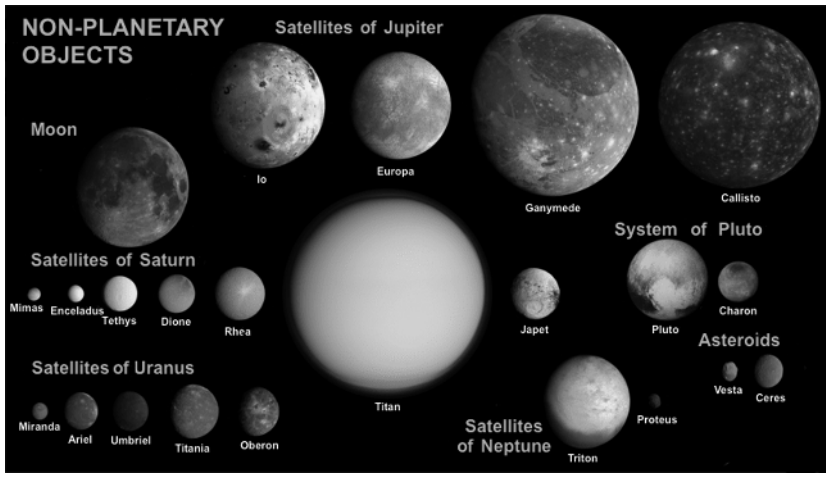


Figure 1.13. *Natural satellites of the giant planets and other non-planetary objects (source: NASA, Planetary Society). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

All of Uranus's inner satellites (those observed by Voyager 2) seem to be composed of about half water ice and half rock. The composition of the satellites outside Oberon's orbit remains unknown, but they are probably captured asteroids. Each of these satellites has unique characteristics. *Miranda*, the smallest and innermost of the five large satellites, has a surface that does not resemble that of any other satellite. It has giant canyons, up to 12 times deeper than the Grand Canyon, layers and terraces that seem very old, and others that seem much younger. Their origin on such a small object remains enigmatic. *Ariel* has the brightest and possibly the youngest surface of all of Uranus's satellites. This satellite has few large craters and many small ones, which indicates that relatively recent weak impacts have erased the large craters that would have been left by older and larger impacts. Valleys dotted with craters and crescents mark its surface.

Umbriel is old and the darkest of the five large satellites. It has many ancient large craters and harbors a mysterious bright ring on one side. *Oberon*, the outermost of the five large satellites, is old, highly cratered, and shows few signs of internal activity. An unidentified dark material appears on the floor of several of its craters. Finally, *Cordelia* and *Ophelia* are *ring shepherds* that guard Uranus's thin epsilon ring. Between them and *Miranda* are found a set of eight small satellites that do not resemble any other planetary satellite systems. This region is so crowded that astronomers fail to understand how these small satellites have avoided being smashed. They may be some of the shepherds for the planet's 10 narrow rings, and scientists think that there must be more satellites, closer than those already known, to constrain the edges of the interior rings.

1.4.2. *The satellites of Neptune*

British astronomer William Lassell (1790–1880) discovered Triton on October 10, 1846, just 17 days after the discovery of Neptune (Cruikshank 2016). Scientists using powerful telescopes and spacecraft have since discovered a total of 14 satellites in orbit around the planet. *Triton* is by far the largest of Neptune's satellites (see Figure 1.13). Gerard Kuiper discovered *Nereid* in 1949. *Proteus*, which is much larger than Nereid, and five other satellites, had to wait for Voyager 2 to be known.

Other than Triton, Neptune's satellites are some of the darkest in the Solar System. The astronomers using the most powerful ground-based telescopes discovered more satellites in 2002 and 2003. Proteus is a slightly aspherical satellite, and we think that it is at the limit of the size for an object before its gravity imparts a spherical form.

The Voyager 2 mission revealed to us the atmosphere and the surface of Triton during its flyby of Neptune in 1989. Before this date, ground-based infrared spectroscopy had shown the presence of CH_4 and N_2 ice on the surface, but its atmosphere was unknown. Voyager 2 measured a density of 2.08 g/cm^3, a surface temperature of 38 K, and a surface pressure of 14 μbar (140 Pa). The presence of ice is responsible for its high albedo (0.7). The existence of a stable atmosphere is made possible by the very low temperature, which limits gravitational escape. Triton's atmosphere, which is unique in the Solar System, is made up of a troposphere up to an altitude of 8 km, topped by a thermosphere that extends to the ionosphere at 400 km altitude. Traces of aerosols probably resulting from methane and products of photodissociation and nitrogen clouds are also present. Seasonal effects, which are notable on Triton, cause the condensation of N_2 and CH_4, which play an analogous role to CO_2 and H_2O on Mars.

Voyager 2 revealed unexpected details about Triton. Part of its surface is relatively undamaged ((Cruikshank 2016); see also Figure 1.13) while ice volcanoes elsewhere eject what is probably a mixture of liquid nitrogen, methane, and dust, which freezes instantly and falls back to the surface. An image from Voyager 2 showed a glacial plume rising 8 km above the surface and drifting for 140 km with the wind. We do not know its precise origin. Triton moves around its planet in the opposite direction from the planet's rotation (in retrograde orbit), which suggests that it may have been an independent object captured by Neptune. The disruptive effect that this may have had on the other satellites could explain why Nereid has the most eccentric orbit of all known satellites (e = 0.75). Neptune's gravity acts on Triton's retrograde orbit, slowing it and pulling it toward the planet. In a few million years, Triton will reach the Roche limit (see section 1.5.1) and will be destroyed by gravitational forces.

1.4.3. *Future exploration of the icy giant planets' systems*

Even if Uranus and Neptune have been recognized among the priorities of the space agencies' programs, these icy giants remain the only planets not to have been explored in detail, while even Pluto and Charon were recently visited by the New Horizons mission. The brief encounters with Voyager 2 gave us an overview of the complexity and unique character of these planets and finally raised a number of other questions. With new, large telescopes and the exploration by missions (as was the case for Jupiter and Saturn), our knowledge of the systems of Uranus and Neptune should grow. Future missions to Uranus and Neptune should provide us with important new information on the formation of these far-away systems, especially since the measurements from Voyager 2's flyby may not have been representative of their complete seasonal cycles, because of the length of these planets' orbital periods.

1.5. The rings

The first rings were discovered around the planet Saturn by Galileo on July 25, 1610. But Galileo did not understand the structure he saw: "I observed that the farthest planet has a triple form. The planet seems to have handles that appear and disappear." It was Huygens who, in 1659, understood that there was a flat disk surrounding the planet, seen from different angles depending on the date. Two hundred years later, Maxwell showed that this ring cannot be solid, and that it had to be made up of isolated particles. Galileo's instrument, Huygens's physical intuition, and Maxwell's mathematics were all needed for us to be able to grasp the idea of a planetary ring (see Figure 1.14).

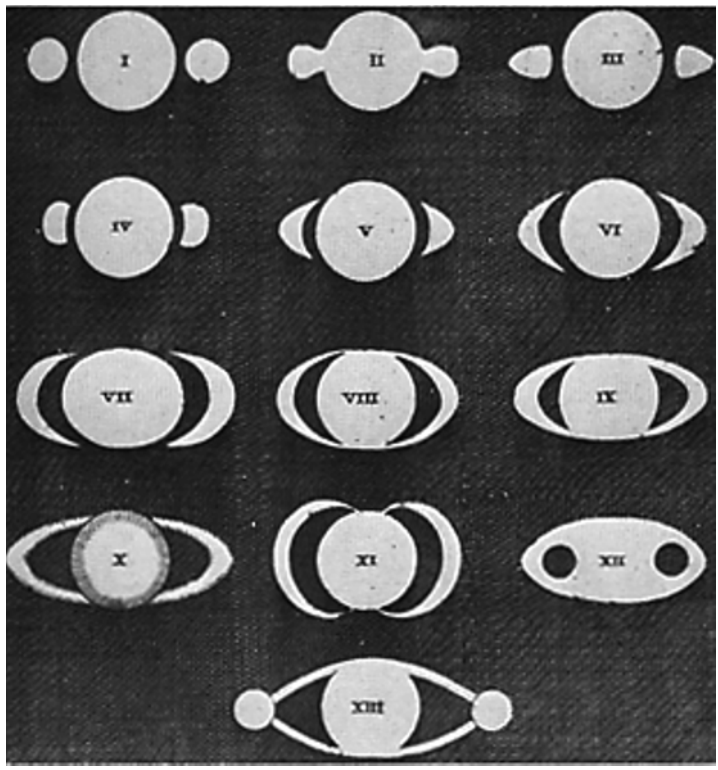


Figure 1.14. *Drawings of Saturn by different observers in the 17th century, before Huygens came to understand that it has a ring. Drawing 1 is Galileo's (source: according to Huygens, Systema Saturnium, p. 202, Library of the Paris Observatory)*

On March 10, 1977, the rings of Uranus were discovered by James Eliot's team by observing an occultation of a star by the planet. The rings appeared as a brief blocking of the star's light before and after its passage behind the planet. Jupiter's rings, which are almost invisible from Earth, were observed for the first time by the Voyager 1 probe when it approached the planet on July 9, 1979. It was not until July 22, 1984 that, as for Uranus, the observation of an occultation of a star by the planet allowed André Brahic's team to discover an arc (incomplete ring) around Neptune.

Thus, all of the giant planets have rings. These four ring systems have very different structures, narrow or wide, bright or dark, composed of particles with sizes ranging from microns to kilometers. Their commonalities are that they are in the planet's equatorial plane and they are very close to a number of small satellites (see Figure 1.15).

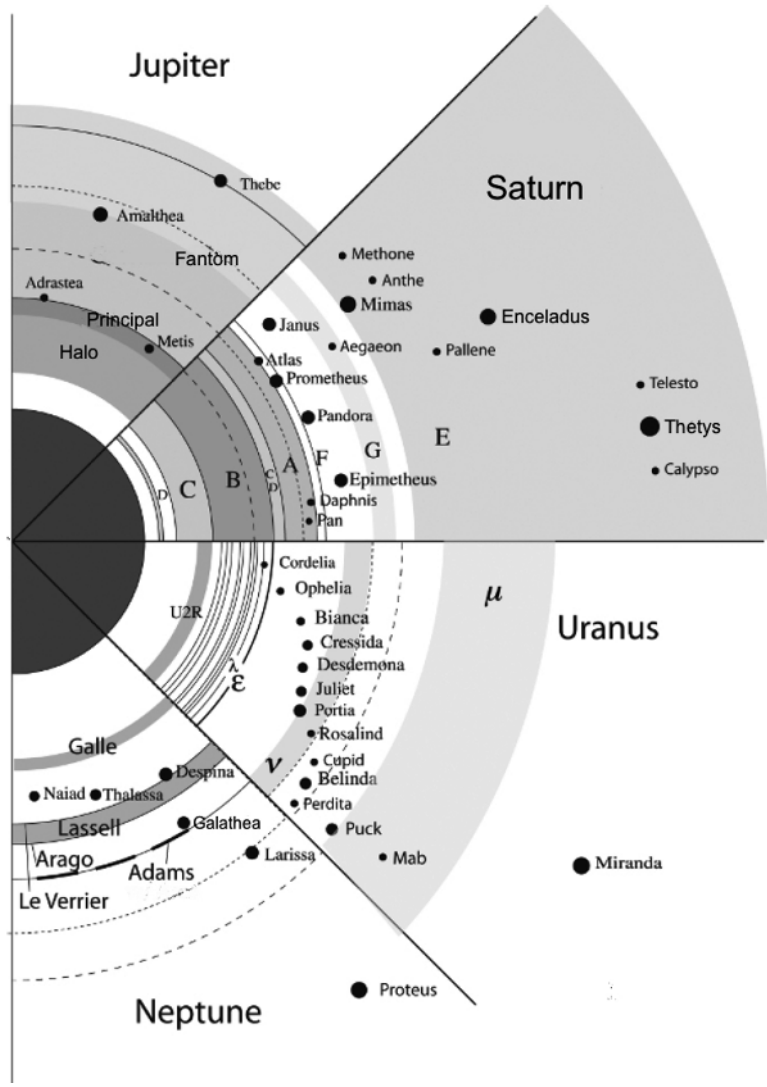


Figure 1.15. *The four ring systems of the giant planets and the near satellites. The different shades of gray indicate the optical depth of the different components. Synchronous rotation is indicated by dotted lines and the Roche limit for the density of water is indicated by dashed lines (source: from (Grun* et al. *2001))*

But rings are not the prerogative of giant planets, since stellar occultations, once again, have allowed us to discover them around the small bodies Chariklo and Haumea, in 2013 and 2017, respectively.

After flybys by the Pioneer and Voyager probes, Cassini, in orbit around Saturn between 2004 and 2017, explored these rings at length. The main result of these observations may be that the rings are shifting, dynamic, evolving systems, but also that they show a number of signs of youth: the bright surface of the rings of Saturn, the small size of the particles in several rings, arcs and confined rings, and the sharp edges. The angular momentum transferred between the rings and the near satellites by density waves translate into a general outward motion from their planet. Because of erosion from meteor impacts, small satellites have short lifetimes in relation to the age of the Solar System, and thus rings accrete into satellites, which themselves crumble into rings. Moreover, satellites shape the rings through gravitational perturbations that are essentially linked to resonances. But paradoxically, these permanent modifications are not necessarily a sign that the rings appeared recently.

Furthermore, the mechanisms observed in the rings are also at work in other flattened astronomical structures, spiral galaxies, or circumstellar disks in which planets form. The (relative) proximity of planetary rings has provided a laboratory for better understanding the dynamics of galaxies and the processes of planetary formation.[14]

1.5.1. *Tidal forces and the Roche limit*

Inside a satellite orbiting a planet, the planet's gravitational attraction is not the same between close and distant points on the satellite. This difference in attraction deforms the satellite, and when the difference between the force at the center of the satellite and at the edges is greater than the satellite's internal forces of cohesion, it will break up. The distance L_R on the planet at which these two forces cancel each other out is called the Roche limit (see section 1.2.7.2, Volume 1 and section 4.8.3 in this volume). Inside this limit, a satellite is unstable and breaks up into a ring, and outside of it, the particles in collision accrete on the satellite, and a ring cannot be maintained.

When an object approaches a planet at a distance lower than L_R, it fragments and gives rise to smaller objects. Their mutual violent collisions reduce the average size of the grains, which progressively populate a ring of matter. The collisions also

14 For a general review, see Greenberg and Brahic (1984); for a more recent review, see Tiscareno and Murray (2018).

reduce the velocity component perpendicular to the planet's equatorial plane and circularize the orbits. This evolution translates into a decrease in energy and a conservation of the particle cloud's angular momentum. The particles quickly find themselves on circular orbits in the equatorial plane. Outside the plane of the equator, particles orbit in precession, which causes collisions and brings the particles back into the equatorial plane. Once the ring has formed, weaker collisions cause it to spread out. In the absence of another disturbance, a part of the ring falls into the planet and the other part extends beyond the Roche limit, where the particles will accrete and form a satellite. Those satellites that are small enough to resist tidal effects remain near the planets and orbit between the rings. On the other hand, diffuse rings spread outside the Roche limit (see Figure 1.15). Images obtained by the Cassini probe show that this region is the site of active mechanisms of collision and accretion.

To estimate the distance from the planet of this limit, we can compare the difference in the gravitational attraction of the planet on two particles to the gravitational attraction they exert on each other. Thus, we find $L_R = 2^{4/3} R_P (\rho/\rho_P)^{1/3}$, R_P being the planet's radius, ρ_P its density, and ρ the satellite's density (see section 4.7.3 of this volume).

1.5.2. *Flattening and ring dispersion*

The study of the dynamics of a disk of colliding particles shows that it flattens rapidly within a time period of a few dozen collisions per particle. It then attains a state of quasi-equilibrium where the combined effect of differential rotation and inelastic collisions will make it spread slowly inward and outward while conserving the system's total angular momentum. In the absence of confining forces, the time to spread is the time it takes the particle to cross the ring in a random path. During collisions, some of the relative velocity due to differential rotation transforms into vertical and radial agitation. Equilibrium is established between the kinetic energy received by differential rotation and that lost through inelastic collisions. Given that the angular momentum is conserved, the energy loss of the particles moving inward is greater than the energy gained by the particles moving outward, and the disk loses a small fraction of its total energy.

1.5.3. *Jupiter's rings*

All of the ring systems include diffuse rings; those of Jupiter are the best example (see (Burns *et al.* 2004) and Figure 1.15). Their structure also shows the strong link that exists between rings and satellites. The densest ring, the *main ring*,

extends inward from the orbit of the satellite Adrastea. Inside the main ring, a toroidal structure is called “the halo”. Outside, two very diffuse rings, the *phantom rings*, are associated respectively with the satellites Amalthea and Thebe.

These rings are very difficult to observe from Earth because of their proximity to the planet. The solar light they scatter is extremely faint in comparison to Jupiter’s luminosity. It is only in very narrow spectral domains, where the Jovian atmosphere is opaque, that ground-based observations of these rings have been carried out. Voyager 2, followed by Galileo, provided details about the properties of Jupiter’s rings. The main ring is the brightest, although its optical depth is very low, on the order of $3\ 10^{-6}$. It extends over 7,000 km between a highly contrasted outer edge at 1.81 R_J (R_J being Jupiter’s radius) and a more diffuse limit at 1.72 R_J. Inside, the halo, with an optical depth of 10^{-6}, extends from 1.72 R_J to Jupiter’s upper atmosphere. The ghost rings, which are even less dense, surround the whole structure.

Lit from behind, the rings are twenty times brighter than in reflected light because of the size of the particles. Between 1 and 15 microns, these particles have very short lifetimes because of the dynamic effects (Poynting-Robinson drag, electromagnetic force, see section 4.9.2) and erosion (ionic and micro-meteorite bombardment, collisions). The rings of Jupiter therefore need to be constantly supplied with new dust. The particles come from the four small satellites, Thebe and Amalthea for the ghost rings and Metis and Adrastea for the main ring and the halo (see section 1.2.2).

1.5.4. *Saturn’s rings*

At the end of the 17th century, the structure of Saturn’s rings began to be observed. In 1675, Cassini discovered that there is not one homogeneous ring, but it is divided into two rings, A and B, separated by the division that bears his name. The inner C ring was discovered in 1850. Laplace showed in 1785 that a solid ring would not be stable under the effects of tidal forces, and this idea was verified theoretically by Maxwell in 1857 and then observationally at the end of the 19th century by measuring the rotation speed using the Doppler-Fizeau effect: the orbital speed of dust particles depends on their distance from Saturn, according to Kepler’s third law. It was only during the 20th century that models managed to describe the evolution of the rings, particularly the effect of collisions between grains. The spectacular data from space probes shows that the rings are constantly evolving systems (Esposito 2010). Thinner and thinner rings have been discovered, both inside the C ring, where the existence of the D ring was confirmed, and outside the A ring (see Figures 1.7 and 1.15): the outermost E ring extends beyond the Roche

limit. The F ring, on the contrary, is only 4,000 km from the A ring. The G ring is in-between. Although the optical depths of the A and B rings are close to 1, that of the E ring is only 10^{-7}. Hundreds of satellites that are a few dozen kilometers in diameter and have low density (0.5 g/cm^2), or accumulations of particles of all sizes, form and disappear, sculpt undulating edges, waves, and helically shaped forms (see Figure 1.16). Several of these satellites have *skirts*, an accumulation of matter fallen from neighboring rings (see also section 1.3.3.2).

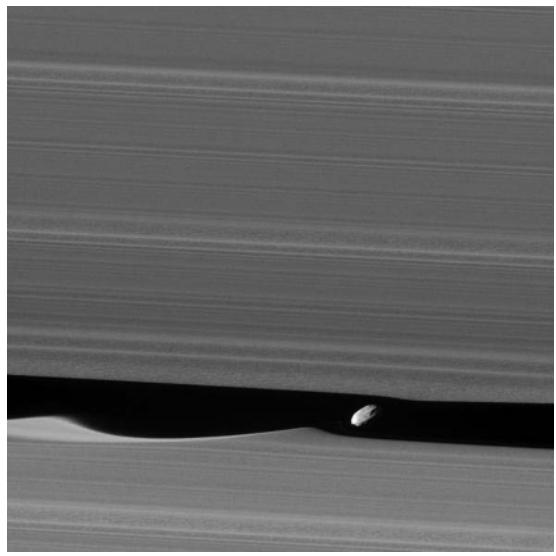


Figure 1.16. *Daphnis and its wave on the edge of the Keeler division, inside the A ring (source: NASA/JPL-Caltech/Space Science Institute)*

At high image resolution, the rings appear in the form of thousands of very thin concentric circles that are clearly distinct. This is also the case in the Cassini division, which is not empty of grains but rather filled with a multitude of rings. At the smallest scale, some rings are twisted or contain heterogeneous regions. Radial structures, dark in reflection but bright in diffusion, change very rapidly over time. With a length that can exceed 10,000 km, they appear in a few minutes and last at most a few dozen hours. They may be submicron particles lifted up during magnetic storms.

The thickness of the rings can be locally very small, limited to the size of a few particles: the dynamic evolution of the rings leads to surprisingly effective planar confinement, if we compare the local thickness of the disk, which is less than a

kilometer, to its diameter, on the order of 300,000 km. However, the rings have vertical excursions that increase their overall thickness. Not only do satellites create vertical undulations, but auto-gravity also creates temporary accumulations of particles that are relatively voluminous. These structures have been particularly highlighted in low-angle light observations by Cassini at the equinox (see Figure 1.17).

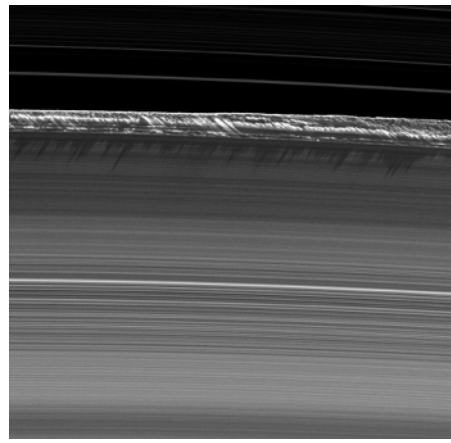


Figure 1.17. *Exterior edge of the B ring confined by 2:1 resonance with Mimas and, above, the beginning of the Cassini division. It is likely that the accumulation of matter favors the formation of large objects whose shadows we see at low angles (source: NASA/JPL-Caltech/Space Science Institute)*

The size of the particles varies widely between the diffuse D, E, F, and G rings and the main rings, where most of the particles range between a centimeter and about a dozen meters, with a power distribution of size with a factor of 3.

As in the case of Jupiter's rings, the presence of small grains with brief lifetimes in Saturn's environment implies the existence of reservoirs and constant renewal. The rings undergo constant dynamic evolution. In particular, gravitational interactions are responsible for heterogeneities of density, structural irregularities, and spiral density waves. These interactions as a whole, operating on grains that are constantly subjected to collisions, lead in the end to a stable confinement of these grains.

Crystalline water ice is the rings' primary component. A reddening of the rings' spectra greater than that on the surface of the satellites may be a sign of the presence

of organic matter, iron, or carbon. The color changes under bombardment by meteors and with the interaction of the particles with the magnetosphere and the ionosphere. The interpretation of spectroscopic observations depends on complex models that take into account distributions of sizes, shapes, temperature, and particle composition. Significant variations in color appear between the rings, but we have not yet been able to connect them to the chemical composition of the grains. They indicate, on the other hand, that the motion of grains from one ring to another is not a dominant process, which confirms the stability of Saturn's ring system.

1.5.5. *Uranus's rings*

The rings of Uranus (French *et al.* 1991) were discovered on March 10, 1977, during a stellar occultation by the planet. They have been studied since then using the same technique, with the first direct photograph taken in 1984. In total, 10 very narrow rings have thus been discovered, located between 42,000 and 52,000 km from the planet's center (see Figure 1.15). They are named based on their increasing distance from Uranus, first by number: 6, 5, 4, then by Greek letters, α, β, η, γ, δ, λ, and ε. All are less than 100 km thick, and eight of them are less than 10 km thick. Their albedo is particularly low, below 5%. There are also three wide and diffuse rings, ζ, η, and μ. All of these rings are immersed in a compound, visible only through forward scattered light, which has an optical depth on the order of 0.005.

The ε ring's thickness varies from 20 to 100 km. The rings are primarily made up of grains that range from a few centimeters to a few meters wide, except for λ, which is made up of dust. The very low albedo of the ring's material may be due to the presence of organic polymers, which result from irradiation of grains of ice containing hydrocarbons by magnetospheric winds. Thirteen small satellites are associated with the rings, eleven of which were discovered by Voyager's flyby in 1986, while the two others were discovered by the Hubble Space Telescope in 2003.

1.5.6. *Neptune's rings*

With the discovery of the rings of Uranus by stellar occultation, the same technique was applied to investigate the rings around Neptune. In 1984, an occultation revealed, in Neptune's vicinity, the presence of a semi-transparent object, 15 km wide and at least 100 km long. It therefore could not be a satellite. Furthermore, no detection was recorded from the other side of the planet, where a complete ring would have interrupted the star's apparent trajectory. This was the first discovery of an incomplete ring, an arc, a structure that was previously unknown and which is unstable if isolated. Indeed, the particles of the inner edge of

a ring rotate more quickly than those on the outer edge. Therefore, without a mechanism for confining them, an arc should spread quickly to form a complete ring. In 1989, Voyager 2, reprogrammed to observe these structures, observed four narrow, diffuse rings made up of micrometer-sized dust ((Porco *et al.* 1995; see also Figures 1.15 and 1.18). The narrow Adams and Le Verrier rings have radii of 62,932 and 53,200 km. The Lassell ring, 4,000 km wide, spreads inward, between the Le Verrier and Arago rings. A very faint ring may share the orbit of the satellite Galatea, 980 km inside the Adams ring. These faint rings are undetectable by occultation.

On the Adams ring, three arcs are superimposed, covering about 40 degrees of longitude and whose optical depth, on the order of 0.1, clearly explains the events seen from Earth. These three arcs are called "Liberté, Egalité, Fraternité". Since Voyager's flyby, Liberté has split into two components, Liberté 1 and Liberté 2, and a fifth arc has appeared, named "Courage".

The Adams ring is located in proximity to the 42:43 mean-motion resonance with the Galatea satellite; in other words, the ring makes exactly 42 revolutions around the planet while the satellite makes 43. The stability of Neptune's arc can be explained by resonant interactions with this satellite, which has an orbit that is both inclined and eccentric (see Figure 1.18).

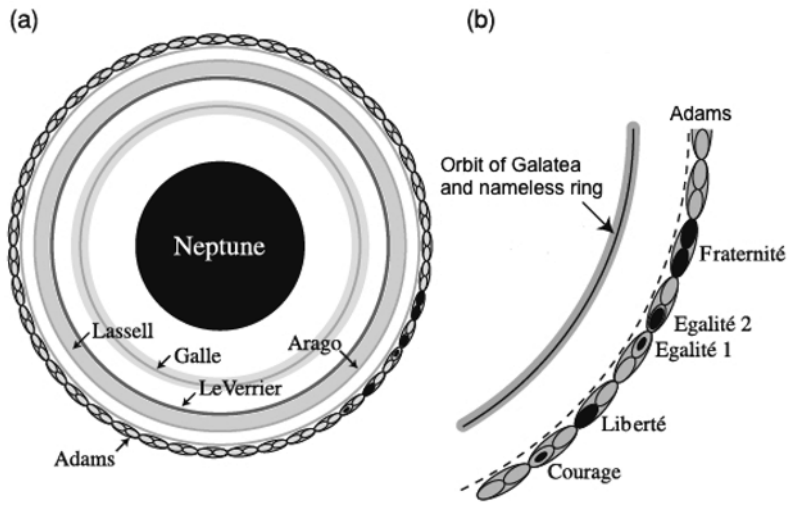


Figure 1.18. *Neptune's rings seen from the south pole (source: (Pater 2015), thanks to C. Murray)*

1.5.7. *The rings of small bodies*

1.5.7.1. *Chariklo-Haumea*

The star occultation technique revealed that the outer Solar System's small bodies can also have rings (see Figure 1.19). In a few years, ring systems have been discovered around at least two of these small bodies, Chariklo and Haumea. The discovery that small bodies a few hundred kilometers wide could be surrounded by dense rings, which we believed to be the prerogative of the giant planets, was an enormous surprise. Chariklo is a 250 km large Centaur orbiting between Saturn and Uranus. It is one of the darkest objects in the Solar System, which became captured in its orbit about 10 million years ago, a very short time compared to the age of the Solar System. The stability of Chariklo's rings requires that the particles have very low density.

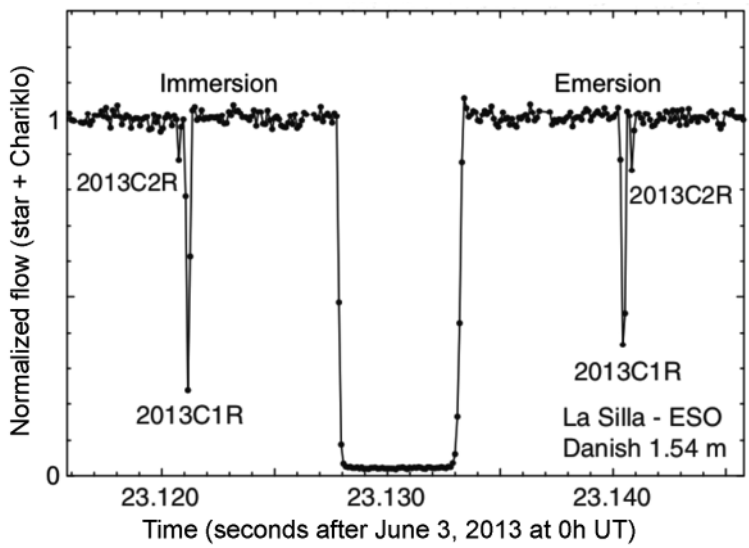


Figure 1.19. *Occultation of a star by the Chariklo system, observed on June 3, 2013: stellar flux over time (source: based on (Sicardy* et al. *2018))*

Haumea is a dwarf planet, one of the largest trans-Neptunian objects known, along with Eris and Pluto. It is an ellipsoid measuring 2,300 km by 1,705 km by 1,035 km, orbiting at 50 astronomical units from the Sun. In January 2017, a stellar occultation revealed the presence of a 70 km wide ring around this dwarf planet, probably in the same orbital plane as the satellite Hi'iaka.

Another centaur, Chiron, may also have rings, even if observations of it could rather be explained by transitory cometary activity.

In the cases of Chariklo and Haumea, the rings are narrow, with sharp edges, which requires a containment mechanism, possibly due to small satellites that have not yet been discovered.

Two orders of magnitude separate the size of planetary rings from these mini-rings, which may nevertheless have similar mechanisms. But differences exist; in particular, the gravity field of these small bodies can exhibit relatively significant irregularities. The departure from sphericity of a planet is limited to its flattening, and so a 5 km high mountain on the surface of Chariklo is equivalent to a satellite of Titan's size near the surface of Saturn. These irregularities create resonances between the rotation period of the particles and the rotation period of the central body. Because of these resonances, the particles inside the co-rotation (the place where the particles rotate at the same speed as the central body) will be slowed down and will fall to the body's surface, and the outer particles will move away from the central body. A 5 km mountain could empty the co-rotation zone in less than a million years. As for Haumea, the body's elongation has a similar effect that is even faster, within a few dozen years.

If the Roche limit is inside the resonances, the ring will quickly pass the Roche limit and be transformed into a satellite. If the Roche limit is outside the resonances, a ring can exist inside the zone between the resonances and the Roche limit. This is possible if the central body is rotating quickly enough on its axis.

Two hypotheses have been proposed to explain the origin of these mini-rings. The first is the capture of a small body that disrupts it as it enters the Roche limit, or after a collision. Another hypothesis is that the matter ejected during outgassing (due to reheating caused, for example, by being closer to the Sun) was slowed and that collisions reduced the energy of the particles to form a ring.

1.5.7.2. *Transitory rings and disks*

In the Solar System, the region between 8 and 20 au can be favorable to stable ice rings around small bodies. Indeed, in this region, ice is too cold to sublimate as it would in a collision closer to the Sun, but is fragile enough to break up in the Roche limit. Furthermore, in this region, the collisions are much less destructive than in the inner Solar System. And finally, this region is favorable to some cometary activity such as what was proposed to explain the matter detected around Chiron and Echeclus.

Mini-rings like those around Chariklo and Haumea probably played a role in the scenario of planetary formation. Crests visible on Rhea and Iapetus (see Figure 1.20 and section 1.3.3.1) may have formed by matter falling from an ancient ring onto the body's equator.

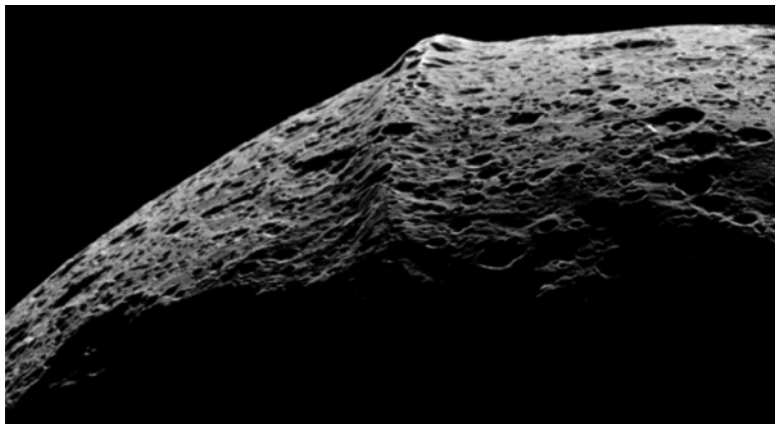


Figure 1.20. *Crest of matter on the surface of Iapetus (source: NASA/JPL-Caltech/Space Science Institute)*

The density of craters on the surface of bodies devoid of atmosphere in the Solar System shows the primordial role of such collisions.

During a collision or a gravitational encounter between two bodies, if a massive enough object stays on, the other bodies will quickly form a ring around this central body. The lifetime of this ring is highly variable depending on the environment. If the system can evolve without too much disturbance, some of the particles will fall on the central body while others will move away quickly, and, once they reach the Roche limit, accrete into a disk. This may explain the large number of double objects in the Kuiper disk. Transitory rings probably also existed in the inner Solar System. For example, the satellites of Mars are in the planet's equatorial plane. They probably formed in a circum-Martian disk that appeared during the capture of planetesimals. The rings discovered around Chariklo and Haumea may be an example of this type of transitory phenomenon, with the particularity that their lifetime must not be too short compared to the age of the Solar System since they were able to be observed.

1.5.8. *Ring dynamics*

All rings present numerous, essentially radial structures with a wide diversity in terms of size. Many are well explained, especially when they are connected to resonances with observed satellites. Some even correspond to resonances with inhomogeneities inside the planet. Many more are still misunderstood, particularly in the vastness of Saturn's rings, the extraordinary beauty of which was revealed to us by the Cassini orbiter (see Figure 1.21).[15]

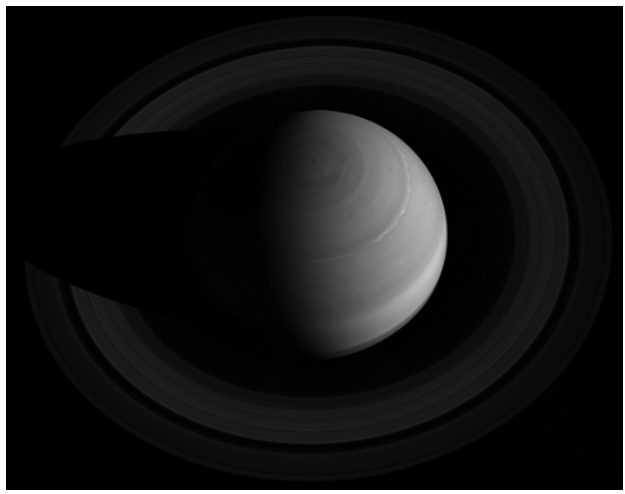


Figure 1.21. *View of Saturn from the Cassini probe in natural colors (as the human eye would see it) (source: NASA/JPL-Caltech/SSI/Cornell). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

1.5.8.1. *Resonances*

When an oscillator is excited by a variable force whose frequency is almost equal to the oscillator's natural frequency, the disturbance can be significant, even for a low amplitude force. This is the case in planetary rings disturbed by satellites whose mass is very small compared to the planet.

There is resonance when the radial frequency of the particles is equal to the frequency of the satellite's horizontal component of force in a rotating frame with

15 See also: https://solarsystem.nasa.gov/missions/cassini/galleries/images/?page=0&per_page=25&order=created_at+desc&search=&tags=cassini&condition_1=1%3Ais_in_resource_list&category=51.

the particle. For these particles, the satellite is disturbed when the particles are in the same phase as its radial oscillation, whose amplitude is subsequently amplified. The particles closest to the exact location of the resonance have the greatest eccentricity. This eccentricity forced by resonance decreases as a function of distance from the resonance.

A similar effect takes place when a vertical oscillation of particles is forced by resonance with a satellite on an inclined orbit, which creates a wave. The precise location where the radial/vertical resonance manifests may be shifted by precession along the lines of apsides/regression of nodes. The effect of this shift is that the horizontal resonances will be found outside the vertical resonances (see the 5:3 resonance with Mimas on Figure 1.22).

Collisions and self-gravity between particles complicate the phenomenon somewhat. Resonant forcing translates into a secular transfer of angular momentum between the ring and its satellites, which can translate into density waves/vertical undulations, empty rings, or sharp edges. This will depend on the respective forces of the satellite and the viscous torque at the location of the resonance in the ring.

The two most important phenomena in Saturn's rings are the confinement of the outer border of the B ring by the 2:1 horizontal resonance with Mimas and the maintenance of the outer border of the A ring by the 7:6 resonance with the co-orbital satellites Janus and Epimetheus. Moderated torque of the same intensity can open empty rings in the C ring with low optical depth but can only generate waves in the A and B rings, which are denser.

Six undulations and about a hundred density waves have been detected in Saturn's rings. These waves are tightly coiled in on themselves (see Figure 1.22), with a typical wavelength of 10 km. The study of these waves has made it possible to estimate the surface density of the rings at 300–600 kg/m^2 in the A and B rings and at 10 kg/m^2 in the C ring or the Cassini division.

The torque applied by the rings on the small satellites causes them to migrate outward on a short time scale compared to the age of the Solar System. Although they are slowed by resonances with more massive outer satellites, Saturn's small satellites like Pandora, Epimetheus, and Prometheus were in the rings a few million years ago.

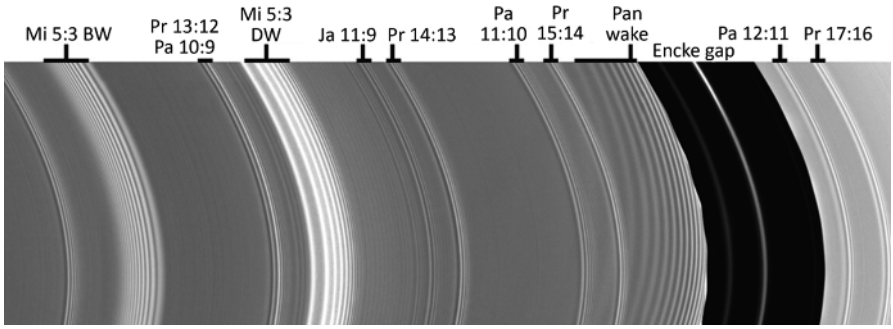


Figure 1.22. *Outer section of Saturn's A ring with a density wave (DW) and a spiral wave (BW) created by the 5:3 resonance with Mimas, as well as other waves associated with Pandora, Prometheus, and Janus (the resonances are indicated). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

COMMENTS ON FIGURE 1.22. – *The dark portion to the right is the Encke division (320 km), which contains several small rings. The wavy and spiral edges (wake) visible inside the division are caused by the recent passage of the satellite Pan (source: Lovett, NASA/JPL/CICLOPS).*

1.5.8.2. *Sharp edges*

The rings of Saturn and Uranus have particularly sharp edges corresponding to orbits in resonance with known satellites. The inner and outer edges of Uranus's ε ring are respectively confined by the 14:13 Lindblad resonance with Ophelia and the 24:25 resonance with Cordelia. The shepherd satellites of Uranus's other narrow rings have not been seen, either because they are too small to be detected or because there are other mechanisms of confinement. Saturn's F ring also has two shepherd satellites, Prometheus and Pandora, but its position does not correspond exactly to the position of equilibrium expected based on calculations. It is possible that the hypotheses made about the distribution of matter in the ring, which is included in the calculation, need to be revisited. Whatever the case, the ring and its two shepherds are migrating outward because of density waves provoked by Prometheus and Pandora in the A ring, and they are going to crash into Mimas in about 20 million years.

1.5.8.3. *Dust*

The dust rings, that is to say, the rings of Jupiter and Neptune, and the E and G rings of Saturn, have unusual dynamics. The particles in the rings are subjected to two effects:

– *Solar radiation pressure*, which pushes particles out of the Solar System. Since this is proportional to the grain's surface, while gravitational attraction is proportional to its volume, radiation pressure is particularly effective on small particles, on the order of a micrometer;

– The *Poynting-Robertson effect* (see section 4.9.2), which results from the fact that a particle in orbit around the Sun receives solar radiation along this axis but re-emits photons isotropically in its own frame. The result is preferential forward radiation (the photons finding their frequency increased because of the speed of the particle), which translates into a loss of energy for the particle. This method of slowing the pace, which constantly diminishes the eccentricity of the grain's elliptical trajectory, tends to drive it to become circular and ends up leading to a spiral trajectory. We thus calculate that a one-micrometer grain subjected to the Poynting-Robertson effect alone would fall into the Sun in a few thousand years. In practice, micrometer-sized grains are more sensitive to radiation pressure, which pushes them out of the Solar System. The Poynting-Robertson effect is therefore especially important for centimeter-sized particles.

1.5.9. *The origin of the rings*

It is very difficult to know the age and the way in which the rings formed, but we can estimate the time scale for the mechanisms that modify them. The dust that makes up Jupiter's rings is slowed by the Poynting-Robertson effect or ejected from the ring system by radiation pressure. Their lifetime is very short, on the order of a few million years. The rings are therefore constantly being resupplied by dust coming from the satellites. The arcs of Neptune are also structures that change over very short time scales, since a new arc has appeared in a few years. It is likely that they were created by collisions between large particles.

The visible arcs may be the visualization in dust of collisions between undetected bodies. The dust rings are therefore transitory structures associated with satellites. The rings of Uranus and Saturn are above all composed of large particles that are much less sensitive to non-gravitational forces. They nevertheless are subjected to the processes of erosion: radiation pressure, meteorite impacts, slowing by the exosphere of the planet. The calculation of the time scale of these phenomena for the rings of Uranus shows that particles are destroyed in a few million years. The particles of Saturn's rings are particularly bright. If they were more than 100 million years old, they would have been darkened by material from the meteorites that bombard the rings. But the particles can be constantly reformed in a ring that itself may be much older. In addition, interactions between the edge of the A ring and the

satellites Prometheus and Janus translate into a distancing of the satellite on a time scale of 10 million years.

Did the rings form at the same time as the planets in a circumplanetary disk, or are they the result of more recent events such as the break-up of a satellite or the accretion of interplanetary matter? An origin of the large particles in the rings by accretion of interplanetary bodies does not explain why all of the rings rotate in the same direction. Moreover, the number of errant bodies in the Solar System has largely decreased since the planets formed. The rings may be the result of the break-up of a satellite that was destroyed upon entering the Roche limit or by a collision, then was prevented from reforming into a satellite by tidal effects.

In this scenario, it is difficult to explain how a satellite would have arrived at the Roche limit. Indeed, a mechanism can cause a satellite to fall towards the planet, but this only applies in synchronous rotation (where the satellite is orbiting at the same angular velocity as the planet rotates), but this occurs inside the Roche limit!

The rings' large particles are probably the remnants of a circumplanetary disk that has been destroyed and reformed several times.

These calculations show that the rings as we see them today have changed significantly since the formation of the Solar System 4.56 billion years ago. They may have been destroyed and reformed several times since the origin of the Solar System on time scales of several dozen million years.

A recent origin for the rings of Jupiter, Uranus, and Neptune does not create any theoretical difficulties because they have such low mass, below that of the surrounding small satellites. The problem is greater for the rings of Saturn, whose evolution is essentially controlled by resonant torques between the rings and the satellites. Understanding this phenomenon is therefore critical to understanding the origin of the rings of Saturn.

The same phenomena of the transfer of angular momentum via resonant torques and density waves plays a determining role in protoplanetary disks (see section 2.4, Volume 1). They govern, for example, the migration of young planets, whose survival we do not understand given the migration times estimated at less than a million years. The key to the formation of the planets may be found in Saturn's rings.

1.5.10. *An exo-ring*

Although thousands of exo-planets have been discovered,[16] none seem to possess rings. It is very possible that this is a result of observational bias.

Indeed, a number of exoplanets are gas giants but they are often very close to their star, which makes the detection of rings difficult and renders the rings probably very fragile. However, a phenomenon observed in 2007 may signal the discovery of exo-rings around a planet of the star J1407.

Indeed, this star's flux has shown variations that could be interpreted as its transit behind an immense ring, 200 times bigger than Saturn's, that surrounds the planet (Kenworthy and Mamajek 2015). As for the planet itself, it has not transited in front of the star (see Figure 1.23). Models show that this type of ring system would not be stable if it is prograde. But if they are retrograde, these rings have a lifetime of more than 10,000 years.

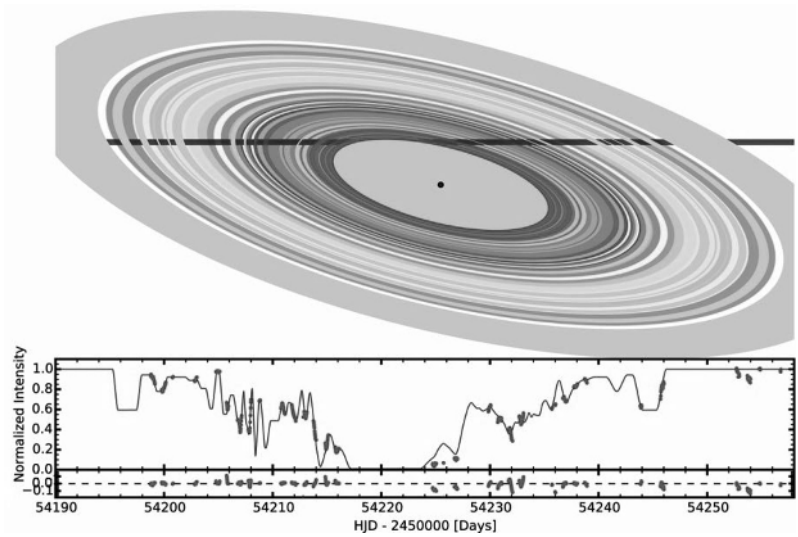


Figure 1.23. *Possible detection by transit of an exo-ring around a planet of the star J1407. Above, a model of the ring and the trajectory of the star at the rear; the planet is represented by a black dot. Below, variations in the star's flux, superimposed on the ring model (source: based on (Kenworthy and Mamajek 2015)). For a color version of this figure, see www.iste.co.uk/encrenaz/solar2.zip*

16 See also: http://exoplanet.eu/catalog/.

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