



12

## Rings, Moons, and Pluto

**Figure 12.1 Jupiter Family.** This montage, assembled from individual Galileo and Voyager images, shows a “family portrait” of Jupiter (with its giant red spot) and its four large moons. From top to bottom, we see Io, Europa, Ganymede, and Callisto. The colors are exaggerated by image processing to emphasize contrasts. (credit: modification of work by NASA)

### Chapter Outline

- 12.1 Ring and Moon Systems Introduced
- 12.2 The Galilean Moons of Jupiter
- 12.3 Titan and Triton
- 12.4 Pluto and Charon
- 12.5 Planetary Rings (and Enceladus)



### Thinking Ahead

Our imaginations always fall short of anticipating the beauty we find in nature.

—Geologist Laurence Soderblom, discussing the 1989 Voyager encounter with Neptune’s moons

All four giant planets are accompanied by moons that orbit about them like planets in a miniature solar system. Nearly 200 moons are known in the outer solar system—too many to name individually or discuss in any detail. Astronomers anticipate that additional small moons await future discovery. We have also discovered a fascinating variety of rings around each of the jovian planets.

Before the Voyager missions, even the largest of the outer-planet moons were mere points of light in our telescopes. Then, in less than a decade, we had close-up images, and these moons became individual worlds for us, each with unique features and peculiarities. The Galileo mission added greatly to our knowledge of the moons of Jupiter, and the Cassini mission has done the same for the Saturn system. In 2015, the NASA New Horizons spacecraft completed the initial exploration of the “classical” planets in the solar system with its flyby of Pluto and its moons. We include Pluto here because in some ways it resembles some of the larger moons in the outer solar system. Each new spacecraft mission has revealed many surprises, as the objects in the outer solar system are much more varied and geologically active than scientists had anticipated.

## 12.1 Ring and Moon Systems Introduced

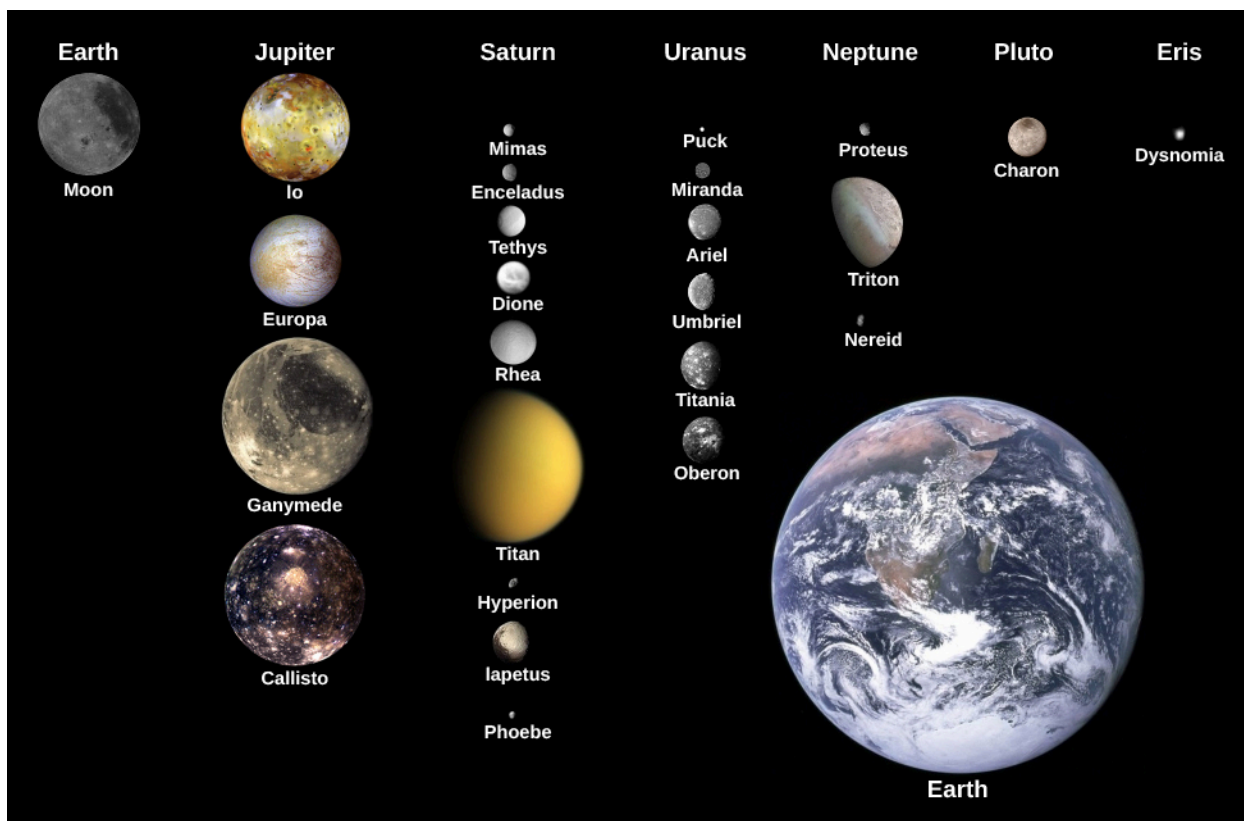
### Learning Objectives

By the end of this section, you will be able to:

- Briefly describe the system of moons around each of the jovian planets
- Describe the basic composition of each jovian planet's ring system

The rings and moons (see the moons in [Figure 12.2](#)) of the outer solar system are not composed of the same materials as the mostly rocky objects in the inner solar system. We should expect this, since they formed in regions of lower temperature, cool enough so that large quantities of water ice were available as building materials. Most of these objects also contain dark, organic compounds mixed with their ice and rock. Don't be surprised, therefore, to find that many objects in the ring and moon systems are both icy and dark.

Roughly a third of the moons in the outer solar system are in *direct* or regular orbits; that is, they revolve about their parent planet in a west-to-east direction and in the plane of the planet's equator. The majority are irregular moons that orbit in a *retrograde* (east-to-west) direction or else have orbits of high eccentricity (more elliptical than circular) or high inclination (moving in and out of the planet's equatorial plane). These irregular moons are mostly located relatively far from their planet; they were probably formed elsewhere and subsequently captured by the planet they now orbit.



**Figure 12.2 Moons of the Solar System.** This image shows some selected moons of our solar system and their comparison to the size of Earth's Moon and Earth itself. (credit: modification of work by NASA)

### The Jupiter System

Jupiter has 79 known moons (that's the number as we write) and a faint ring. These include four large moons—Callisto, Ganymede, Europa, and Io (see [Figure 12.1](#))—discovered in 1610 by Galileo and therefore often called the *Galilean moons*. The smaller of these, Europa and Io, are about the size of our Moon, while the larger, Ganymede and Callisto, are about the same size as the planet Mercury. Most of Jupiter's moons are much smaller. The majority are in retrograde orbits more than 20 million kilometers from Jupiter; these are

very likely small captured asteroids.

## The Saturn System

Saturn has at least 82 known moons in addition to a magnificent set of rings. The largest of the moons, Titan, is almost as big as Ganymede in Jupiter's system, and it is the only moon with a substantial atmosphere and lakes or seas of liquid hydrocarbons (such as methane and ethane) on the surface. Saturn has six other large regular moons with diameters between 400 and 1600 kilometers, a collection of small moons orbiting in or near the rings, and many captured strays similar to those of Jupiter. Mysteriously, one of Saturn's smaller moons, Enceladus, has active geysers of water being expelled into space.

The rings of Saturn, one of the most impressive sights in the solar system, are broad and flat, with a few major and many minor gaps. They are not solid, but rather a huge collection of icy fragments, all orbiting the equator of Saturn in a traffic pattern that makes rush hour in a big city look simple by comparison. Individual ring particles are composed primarily of water ice and are typically the size of ping-pong balls, tennis balls, and basketballs.

## The Uranus System

The ring and moon system of Uranus is tilted at 98°, just like the planet itself. It consists of 11 rings and 27 currently known moons. The five largest moons are similar in size to the six regular moons of Saturn, with diameters of 500 to 1600 kilometers. Discovered in 1977, the rings of Uranus are narrow ribbons of dark material with broad gaps in between. Astronomers suppose that the ring particles are confined to these narrow paths by the gravitational effects of numerous small moons, many of which we have not yet glimpsed.

## The Neptune System

Neptune has 14 known moons. The most interesting of these is Triton, a relatively large moon in a retrograde orbit—which is unusual. Triton has a very thin atmosphere, and active eruptions were discovered there by Voyager in its 1989 flyby. To explain its unusual characteristics, astronomers have suggested that Triton may have originated beyond the Neptune system, as a dwarf planet like Pluto. The rings of Neptune are narrow and faint. Like those of Uranus, they are composed of dark materials and are thus not easy to see.

## 12.2 The Galilean Moons of Jupiter

### Learning Objectives

By the end of this section, you will be able to:

- Describe the major features we can observe about Callisto and what we can deduce from them
- Explain the evidence for tectonic and volcanic activity on Ganymede
- Explain what may be responsible for the unusual features on the icy surface of Europa
- Describe the major distinguishing characteristic of Io
- Explain how tidal forces generate the geological activity we see on Europa and Io

From 1996 to 1999, the Galileo spacecraft careered through the jovian system on a complex but carefully planned trajectory that provided repeated close encounters with the large Galilean moons. More recently, the Juno spacecraft, also a Jupiter orbiter, has provided a few close looks at Ganymede and Europa. (Beginning in 2004, we received an even greater bonanza of information about Titan, obtained from the Cassini spacecraft and its Huygens probe, which landed on its surface. We include Titan, Saturn's one big moon, here for comparison.) [Table 12.1](#) summarizes some basic facts about these large moons (plus our own Moon for comparison).

The Largest Moons

Name	Diameter (km)	Mass (Earth's Moon = 1)	Density (g/cm <sup>3</sup> )	Reflectivity (%)
Moon	3476	1.0	3.3	12
Callisto	4820	1.5	1.8	20
Ganymede	5270	2.0	1.9	40
Europa	3130	0.7	3.0	70
Io	3640	1.2	3.5	60
Titan	5150	1.9	1.9	20

Table 12.1

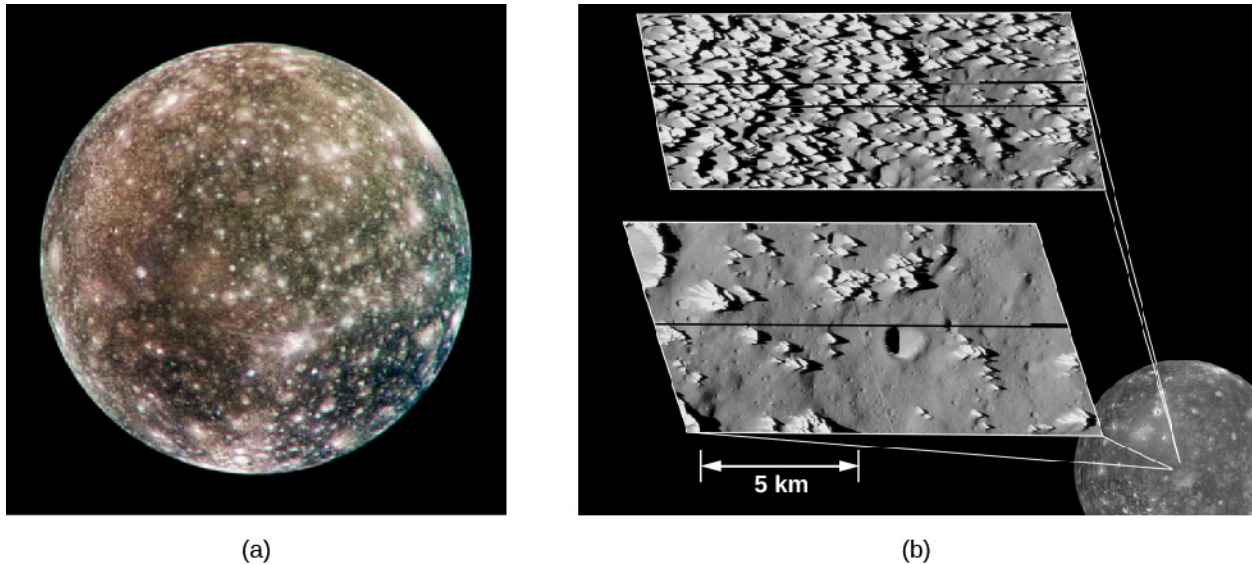
### Callisto: An Ancient, Primitive World

We begin our discussion of the Galilean moons with the outermost one, Callisto, not because it is remarkable but because it is not. This makes it a convenient object with which other, more active, worlds can be compared. Its distance from Jupiter is about 2 million kilometers, and it orbits the planet in 17 days. Like our own Moon, Callisto rotates in the same period as it revolves, so it always keeps the same face toward Jupiter. Callisto's day thus equals its month: 17 days. Its noontime surface temperature is only 130 K (about 140 °C below freezing), so that water ice is stable (it never evaporates) on its surface year round.

Callisto has a diameter of 4820 kilometers, almost the same as the planet Mercury ([Figure 12.3](#)). Yet its mass is only one-third as great, which means its density (the mass divided by the volume) must be only one-third as great as well. This tells us that Callisto has far less of the rocky and metallic materials found in the inner planets and must instead be an icy body through much of its interior. Callisto can show us how the geology of an icy object compares with those made primarily of rock.

Unlike the worlds we have studied so far, Callisto has not fully *differentiated* (separated into layers of different density materials). We can tell that it lacks a dense core from the details of its gravitational pull on the Galileo spacecraft. This surprised scientists, who expected that all the big icy moons would be differentiated. It should be easier for an icy body to differentiate than for a rocky one because the melting temperature of ice is so low. Only a little heating will soften the ice and get the process started, allowing the rock and metal to sink to the center while the slushy ice floats to the surface. Yet Callisto seems to have frozen solid before the process of differentiation was complete.

The surface of Callisto is covered with impact craters, like the lunar highlands. The survival of these craters tells us that an icy object can retain impact craters on its surface. Callisto is unique among the planet-sized objects of the solar system in the apparent absence of interior forces to drive geological change. You might say that this moon was stillborn, and it has remained geologically dead for more than 4 billion years ([Figure 12.3](#)).



**Figure 12.3 Callisto.** (a) Jupiter’s outermost large moon shows a heavily cratered surface. Astronomers believe that the bright areas are mostly ice, while the darker areas are more eroded, ice-poor material. (b) These high-resolution images, taken by NASA’s Galileo spacecraft in May 2001, show the icy spires (top) on Callisto’s surface, with darker dust that has slid down as the ice erodes, collecting in the low-lying areas. The spires are about 80 to 100 meters tall. As the surface erodes even further, the icy spires eventually disappear, leaving impact craters exposed, as shown in the lower image. (credit a: modification of work by NASA/JPL/DLR; credit b: modification of work by NASA/JPL/Arizona State University, Academic Research Lab)

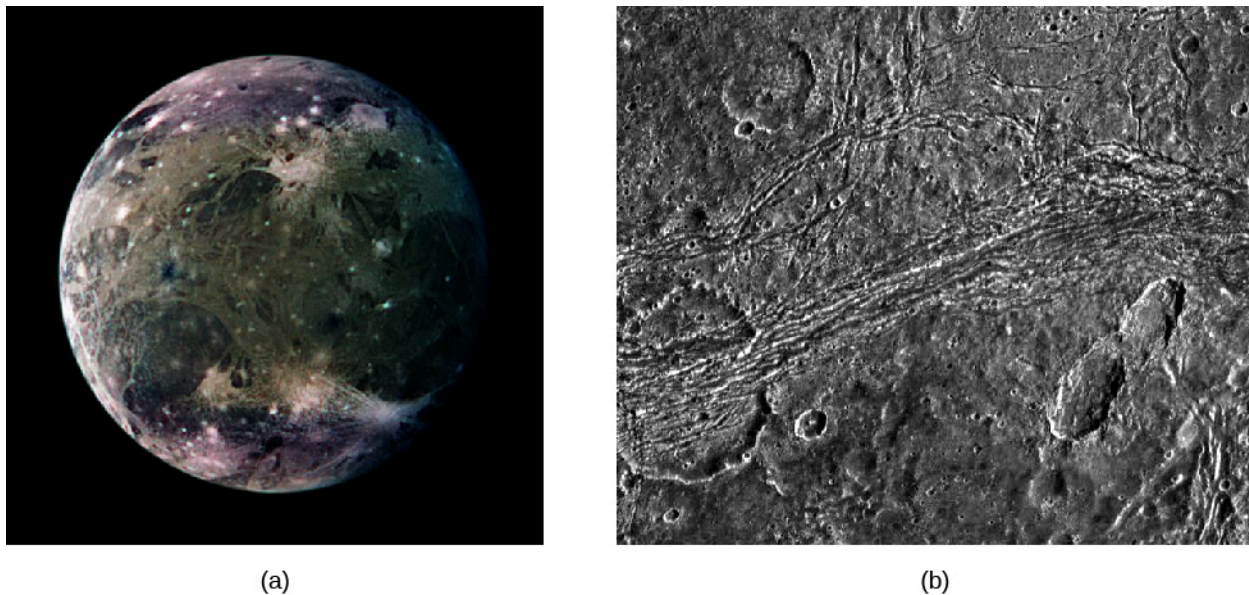
In thinking about ice so far from the Sun, we must take care not to judge its behavior from the much warmer ice we know and love on Earth. At the temperatures of the outer solar system, ice on the surface is nearly as hard as rock, and it behaves similarly. Ice on Callisto does not deform or flow like ice in glaciers on Earth.

### Ganymede, the Largest Moon

Ganymede, the largest moon in the solar system, also shows a great deal of cratering ([Figure 12.4](#)). Recall from [Other Worlds: An Introduction to the Solar System](#) that we can use crater counts on solid worlds to estimate the age of the surface. The more craters, the longer the surface has been exposed to battering from space, and the older it must therefore be. About one-quarter of Ganymede’s surface seems to be as old and heavily cratered as that of Callisto; the rest formed more recently, as we can tell by the sparse covering of impact craters as well as the relative freshness of those craters. If we judge from crater counts, this fresher terrain on Ganymede is somewhat younger than the lunar maria or the martian volcanic plains, perhaps 2 to 3 billion years old.

The differences between Ganymede and Callisto are more than skin deep. Ganymede is a differentiated world, like the terrestrial planets. Measurements of its gravity field tell us that the rock sank to form a core about the size of our Moon, with a mantle and crust of ice “floating” above it. In addition, the Galileo spacecraft discovered that Ganymede has a magnetic field, the sure signature of a partially molten interior. There is very likely liquid water trapped within the interior. Thus, Ganymede is not a dead world but rather a place of intermittent geological activity powered by an internal heat source. Some surface features could be as young as the surface of Venus (a few hundred million years).

The younger terrain was formed by tectonic and volcanic forces ([Figure 12.4](#)). In some places, the crust apparently cracked, flooding many of the craters with water from the interior. Extensive mountain ranges were formed from compression of the crust, forming long ridges with parallel valleys spaced a few kilometers apart. In some areas, older impact craters were split and pulled apart. There are even indications of large-scale crustal movements that are similar to the plate tectonics of Earth.



**Figure 12.4 Ganymede.** (a) This global view of Ganymede, the largest moon in the solar system, was taken by Voyager 2. The colors are enhanced to make spotting differences easier. Darker places are older, more heavily cratered regions; the lighter areas are younger (the reverse of our Moon). The brightest spots are sites of geologically recent impacts. (b) This close-up of Nicholson Regio on Ganymede shows an old impact crater (on the lower left-hand side) that has been split and pulled apart by tectonic forces. Against Ganymede's dark terrain, a line of grooves and ridges appears to cut through the crater, deforming its circular shape. (credit a: modification of work by NASA/JPL/DLR; credit b: modification of work by NASA/JPL/Brown University)

Why is Ganymede so different from Callisto? Possibly the small difference in size and internal heating between the two led to this divergence in their evolution. But more likely the gravity of Jupiter is to blame for Ganymede's continuing geological activity. Ganymede is close enough to Jupiter that *tidal forces* from the giant planet may have episodically heated its interior and triggered major convulsions on its crust.

A tidal force results from the unequal gravitational pull on two sides of a body. In a complex kind of modern dance, the large moons of Jupiter are caught in the varying gravity grip of both the giant planet and each other. This leads to gravitational flexing or kneading in their centers, which can heat them—an effect called **tidal heating**. (A fuller explanation is given in the section on Io.) We will see as we move inward to Europa and Io that the role of jovian tides becomes more important for moons close to the planet.

### Europa, a Moon with an Ocean

Europa and Io, the inner two Galilean moons, are not icy worlds like most of the moons of the outer planets. With densities and sizes similar to our Moon, they appear to be predominantly rocky objects. How did they fail to acquire a majority share of the ice that must have been plentiful in the outer solar system at the time of their formation?

The most probable cause is Jupiter itself, which was hot enough to radiate a great deal of infrared energy during the first few million years after its formation. This infrared radiation would have heated the disk of material near the planet that would eventually coalesce into the closer moons. Thus, any ice near Jupiter was vaporized, leaving Europa and Io with compositions similar to planets in the inner solar system.

Despite its mainly rocky composition, Europa has an ice-covered surface, as astronomers have long known from examining spectra of sunlight reflected from it. In this it resembles Earth, which has a layer of water on its surface, but in Europa's case the water is capped by a thick crust of ice. There are very few impact craters in this ice, indicating that the surface of Europa is in a continual state of geological self-renewal. Judging from crater counts, the surface must be no more than a few million years old, and perhaps substantially less. In terms of its ability to erase impact craters, Europa is more geologically active than Earth.

When we look at close-up photos of Europa, we see a strange, complicated surface ([Figure 12.5](#)). For the most part, the icy crust is extremely smooth, but it is crisscrossed with cracks and low ridges that often stretch for

thousands of kilometers. Some of these long lines are single, but most are double or multiple, looking rather like the remnants of a colossal freeway system.

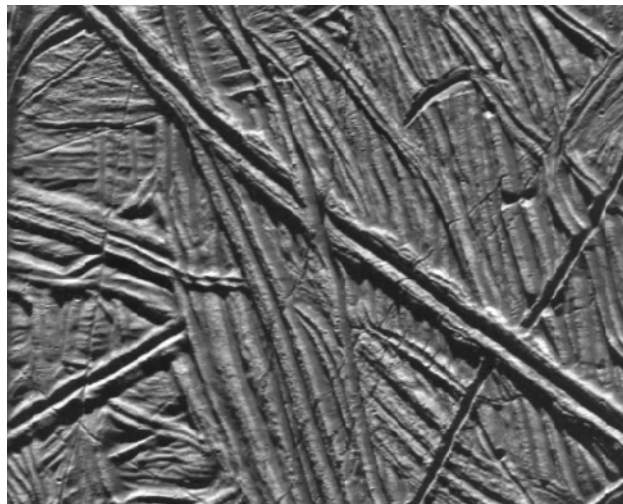


(a)

(b)

**Figure 12.5 Evidence for an Ocean on Europa.** (a) A close-up of an area called Conamara Chaos is shown here with enhanced color. This view is 70 kilometers wide in its long dimension. It appears that Conamara is a region where Europa's icy crust is (or recently was) relatively thin and there is easier access to the possible liquid or slushy ocean beneath. Not anchored to solid crust underneath, many of the ice blocks here seem to have slid or rotated from their original positions. In fact, the formations seen here look similar to views of floating sea-ice and icebergs in Earth's Arctic Ocean. (b) In this high-resolution view, the ice is *wrinkled* and crisscrossed by long ridges. Where these ridges intersect, we can see which ones are older and which younger; the younger ones cross over the older ones. While superficially this system of ridges resembles a giant freeway system on Europa, the ridges are much wider than our freeways and are a natural result of the flexing of the moon. (credit a: modification of work by NASA/JPL/University of Arizona; credit b: modification of work by NASA/JPL)

It is very difficult to make straight lines on a planetary surface. In discussing Mars, we explained that when Percival Lowell saw what appeared to him to be straight lines (the so-called martian "canals"), he attributed them to the engineering efforts of intelligent beings. We now know the lines on Mars were optical illusions, but the lines on Europa are real. These long cracks can form in the icy crust if it is floating without much friction on an ocean of liquid water ([Figure 12.6](#)).



**Figure 12.6 Very High-Resolution Galileo Image of One Young Double Ridge on Europa.** The area in this picture is only 15 kilometers across. It appears to have formed when viscous icy material was forced up through a long, straight crack in the crust. Note how the young ridge going from top left toward bottom right lies on top of older features, which are themselves on top of even older ones. (credit: modification of work by NASA/JPL)

The close-up Galileo images appear to confirm the existence of a global ocean. In many places, the surface of Europa looks just as we would expect for a thick layer of ice that was broken up into giant icebergs and ice floes and then refrozen in place. When the ice breaks, water or slush from below may be able to seep up through the cracks and make the ridges and multiple-line features we observe. Many episodes of ice cracking, shifting, rotating, and refreezing are required to explain the complexity we see. The icy crust might vary in thickness from a kilometer or so up to 20 kilometers. Further confirmation that a liquid ocean exists below the

ice comes from measurements of the small magnetic field induced by Europa's interactions with the magnetosphere of Jupiter. The "magnetic signature" of Europa is that of a liquid water ocean, not one of ice or rock.

If Europa really has a large ocean of liquid water under its ice, then it may be the only place in the solar system, other than Earth, with really large amounts of liquid water.<sup>1</sup> To remain liquid, this ocean must be warmed by heat escaping from the interior of Europa. Hot (or at least warm) springs might be active there, analogous to those we have discovered in the deep oceans of Earth. The necessary internal heat is generated by tidal heating (see the discussion later in this chapter).

### LINK TO LEARNING



A [short film \(https://openstax.org/l/30Europa\)](https://openstax.org/l/30Europa) with planetary scientist Kevin Hand explains why Europa is so interesting for future exploration. Or listen to this [more in-depth talk \(https://openstax.org/l/30Europa2\)](https://openstax.org/l/30Europa2) on Europa.

What makes the idea of an ocean with warm springs exciting is the discovery in Earth's oceans of large ecosystems clustered around deep ocean hot springs. Such life derives all its energy from the mineral-laden water and thrives independent of the sunlight shining on Earth's surface. Is it possible that similar ecosystems could exist today under the ice of Europa?

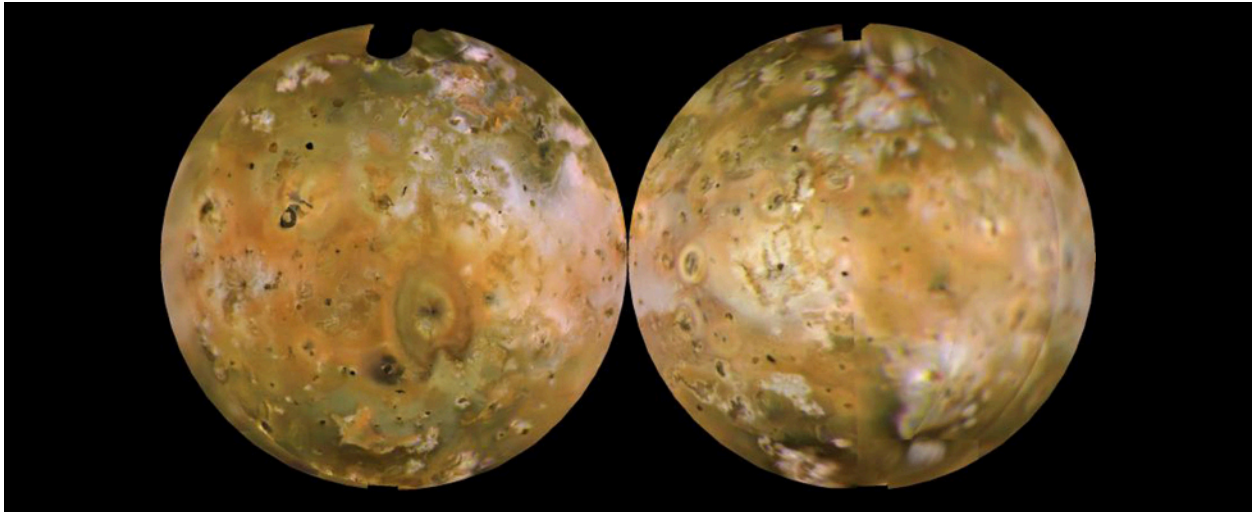
Many scientists now think that Europa is the most likely place beyond Earth to find life in the solar system. In response, NASA is designing a Europa mission to characterize its liquid ocean and its ice crust, and to identify locations where material from inside has risen to the surface. Such interior material might reveal direct evidence for microbial life. This "Europa Clipper" mission will not orbit Europa, where the intense energetic particles from Jupiter's magnetosphere would quickly destroy its electronics, but instead will swoop in for brief close flybys. It is planned for launch in 2024.

### Io, a Volcanic Moon

Io, the innermost of Jupiter's Galilean moons, is in many ways a close twin of our Moon, with nearly the same size and density. We might therefore expect it to have experienced a similar history. Its appearance, as photographed from space, tells us another story, however ([Figure 12.7](#)). Instead of being a dead cratered world, Io turns out to have the highest level of volcanism in the solar system, greatly exceeding that of Earth.

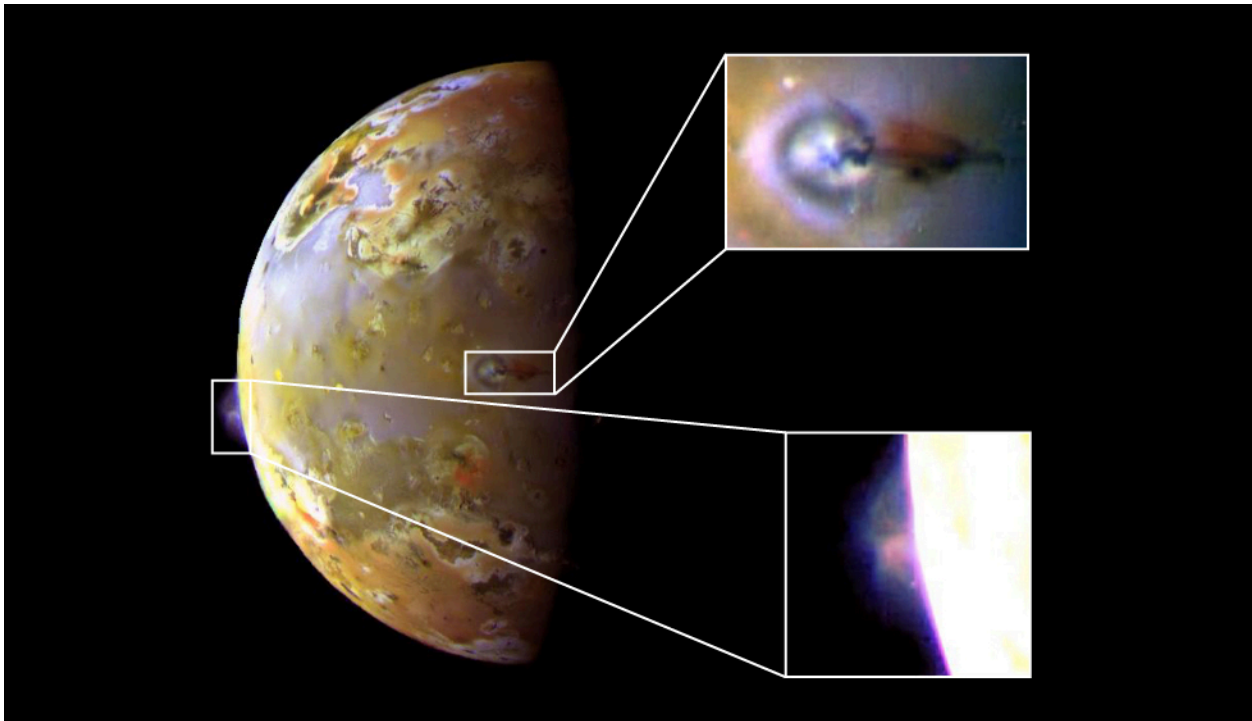
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<sup>1</sup> Ganymede and Saturn's moon Enceladus may have smaller amounts of liquid water under their surfaces.



**Figure 12.7 Two Sides of Io.** This composite image shows both sides of the volcanically active moon Io. The orange deposits are sulfur snow; the white is sulfur dioxide. (Carl Sagan once quipped that Io looks as if it desperately needs a shot of penicillin.) (credit: modification of work by NASA/JPL/USGS)

Io's active volcanism was discovered by the Voyager spacecraft. Eight volcanoes were seen erupting when Voyager 1 passed in March 1979, and six of these were still active four months later when Voyager 2 passed. With the improved instruments carried by the Galileo spacecraft, more than 50 eruptions were found during 1997 alone. Many of the eruptions produce graceful plumes that extend hundreds of kilometers out into space ([Figure 12.8](#)).



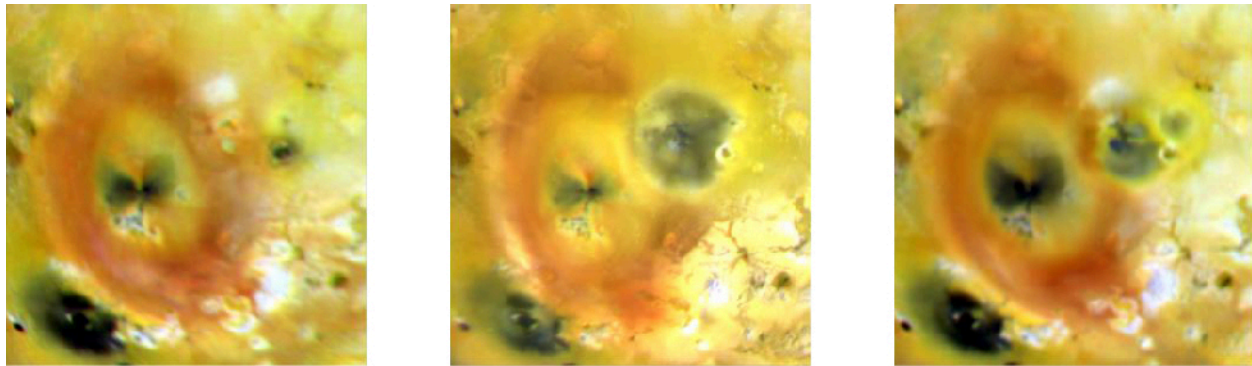
**Figure 12.8 Volcanic Eruptions on Io.** This composite image from NASA's Galileo spacecraft shows close-ups (the two inset photos) of two separate volcanic eruptions on Jupiter's volcanic moon, Io. In the upper inset image, you can see a close up of a bluish plume rising about 140 kilometers above the surface of the volcano. In the lower inset image is the Prometheus plume, rising about 75 kilometers from Io's surface. The Prometheus plume is named for the Greek god of fire. (credit: modification of work by NASA/JPL)

## LINK TO LEARNING



Watch a [brief movie \(https://openstax.org/l/30IoSurf\)](https://openstax.org/l/30IoSurf) made from Voyager and Galileo data, showing a rotating Io with its dramatic surface features.

The Galileo data show that most of the volcanism on Io consists of hot silicate lava, like the volcanoes on Earth. Sometimes the hot lava encounters frozen deposits of sulfur and sulfur dioxide. When these icy deposits are suddenly heated, the result is great eruptive plumes far larger than any ejected from terrestrial volcanoes. As the rising plumes cool, the sulfur and sulfur dioxide recondense as solid particles that fall back to the surface in colorful “snowfalls” that extend as much as a thousand kilometers from the vent. Major new surface features were even seen to appear between Galileo orbits, as shown in [Figure 12.9](#).



April 1997

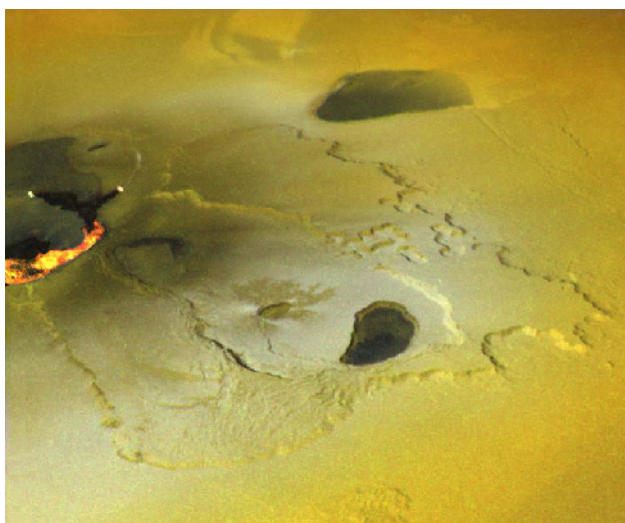
September 1997

July 1999

**Figure 12.9 Volcanic Changes on Io.** These three images were taken of the same 1700-kilometer-square region of Io in April 1997, September 1997, and July 1999. The dark volcanic center called Pillan Patera experienced a huge eruption, producing a dark deposit some 400 kilometers across (seen as the grey area in the upper center of the middle image). In the right image, however, some of the new dark deposit is already being covered by reddish material from the volcano Pele. Also, a small unnamed volcano to the right of Pillan has erupted since 1997, and some of its dark deposit and a yellow ring around it are visible on the right image (to the right of the grey spot). The color range is exaggerated in these images. (credit: modification of work by NASA/JPL/University of Arizona)

As the Galileo mission drew to a close, controllers were willing to take risks in getting close to Io. Approaching this moon is a dangerous maneuver because the belts of atomic particles trapped in Jupiter’s magnetic environment are at their most intense near Io’s orbit. Indeed, in its very first pass by Io, the spacecraft absorbed damaging radiation beyond its design levels. To keep the system working at all, controllers had to modify or disable various fault-protection software routines in the onboard computers. In spite of these difficulties, the spacecraft achieved four successful Io flybys, obtaining photos and spectra of the surface with unprecedented resolution.

Maps of Io reveal more than 100 recently active volcanoes. Huge flows spread out from many of these vents, covering about 25% of the moon’s total surface with still-warm lava. From these measurements, it seems clear that the bright surface colors that first attracted attention to Io are the result of a thin veneer of sulfur compounds. The underlying volcanism is driven by eruptions of molten silicates, just like on Earth ([Figure 12.10](#)).



**Figure 12.10 Lava Fountains on Io.** Galileo captured a number of eruptions along the chain of huge volcanic calderas (or pits) on Io called Tvashtar Catena in this false-color image combining infrared and visible light. The bright orange-yellow areas at left are places where fresh, hot lava is erupting from below ground. (credit: modification of work by NASA/JPL)

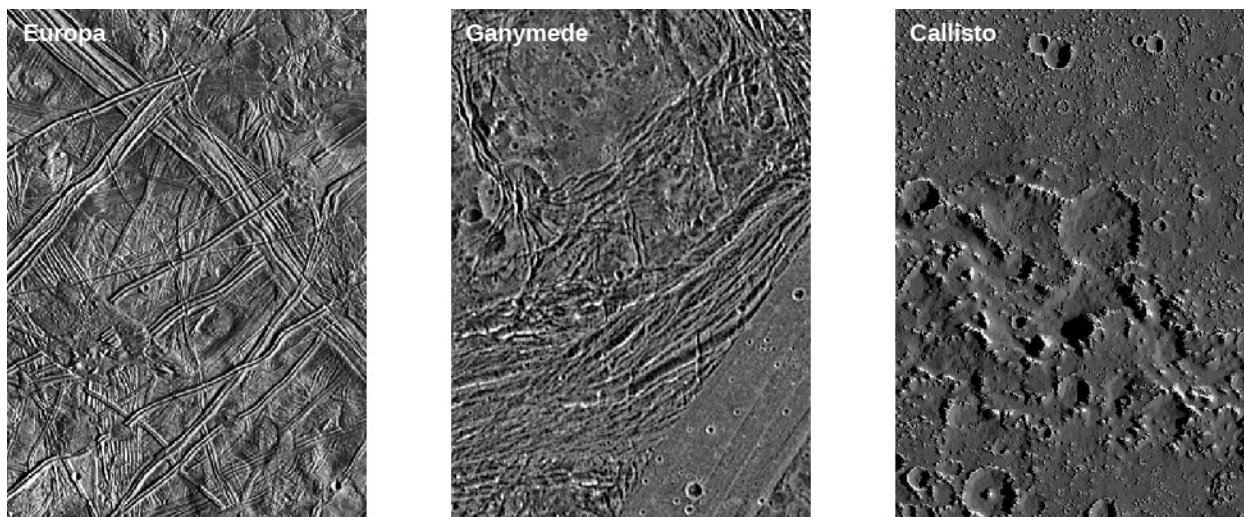
### Tidal Heating

How can Io remain volcanically active in spite of its small size? The answer, as we hinted earlier, lies in the effect of gravity, through tidal heating. Io is about the same distance from Jupiter as our Moon is from Earth. Yet Jupiter is more than 300 times more massive than Earth, causing forces that pull Io into an elongated shape, with a several-kilometer-high bulge extending toward Jupiter.

If Io always kept exactly the same face turned toward Jupiter, this bulge would not generate heat. However, Io's orbit is not exactly circular due to gravitational perturbations (tugs) from Europa and Ganymede. In its slightly eccentric orbit, Io twists back and forth with respect to Jupiter, at the same time moving nearer and farther from the planet on each revolution. The twisting and flexing heat Io, much as repeated flexing of a wire coat hanger heats the wire.

After billions of years, this constant flexing and heating have taken their toll on Io, driving away water and carbon dioxide and other gases, so that now sulfur and sulfur compounds are the most volatile materials remaining. Its interior is entirely melted, and the crust itself is constantly recycled by volcanic activity.

In moving inward toward Jupiter from Callisto to Io, we have encountered more and more evidence of geological activity and internal heating, culminating in the violent volcanism on Io. Three of these surfaces are compared in [Figure 12.11](#). Just as the character of the planets in our solar system depends in large measure on their distance from the Sun (and on the amount of heat they receive), so it appears that distance from a giant planet like Jupiter can play a large role in the composition and evolution of its moons (at least partly due to differences in internal heating of each moon by Jupiter's unrelenting tidal forces).



**Figure 12.11 Three Icy Moons.** These Galileo images compare the surfaces of Europa, Ganymede, and Callisto at the same resolution. Note that the number of craters (and thus the age of the surface we see) increases as we go from Europa to Ganymede to Callisto. The Europa image is one of those where the system of cracks and ridges resembles a freeway system. (credit: modification of work by NASA/JPL/DLR)

## 12.3 Titan and Triton

### Learning Objectives

By the end of this section, you will be able to:

- Explain how the thick atmosphere of Titan makes bodies of liquid on its surface possible
- Describe what we learned from the landing on Titan with the Huygens probe
- Discuss the features we observed on the surface of Triton when Voyager 2 flew by

We shift our attention now to small worlds in the more distant parts of the solar system. Saturn’s large moon Titan turns out to be a weird cousin of Earth, with many similarities in spite of frigid temperatures. The Cassini observations of Titan have provided some of the most exciting recent discoveries in planetary science. Neptune’s moon Triton also has unusual characteristics and resembles Pluto, which we will discuss in the following section.

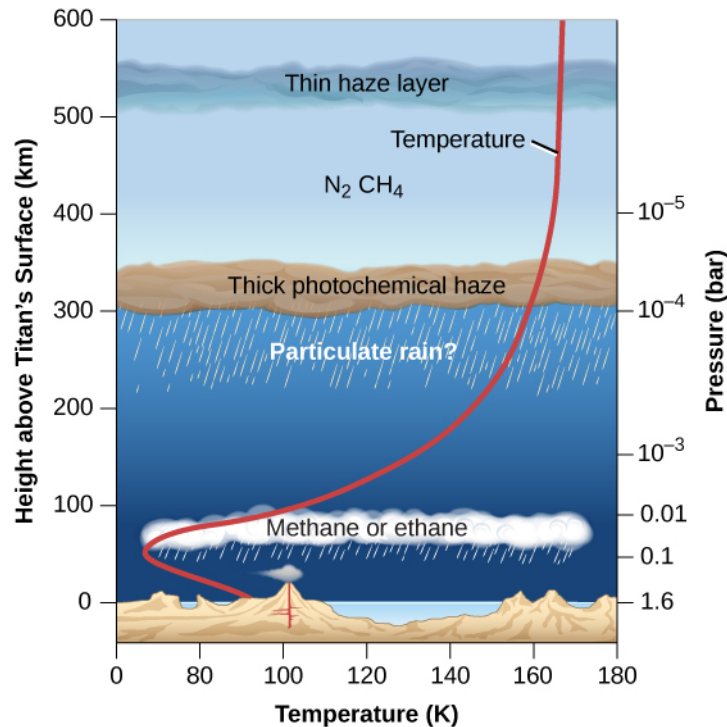
### Titan, a Moon with Atmosphere and Hydrocarbon Lakes

Titan, first seen in 1655 by the Dutch astronomer Christiaan Huygens, was the first moon discovered after Galileo saw the four large moons of Jupiter. Titan has roughly the same diameter, mass, and density as Callisto or Ganymede. Presumably it also has a similar composition—about half ice and half rock. However, Titan is unique among moons, with a thick atmosphere and lakes and rivers and falling rain (although these are not composed of water but of hydrocarbons such as ethane and methane, which can stay liquid at the frigid temperatures on Titan). Titan is the only moon or planet other than Earth where we have found evidence of bodies of surface liquids.

The 1980 Voyager flyby of Titan determined that the surface density of its atmosphere is four times greater than that on Earth. The atmospheric pressure on this moon is 1.6 bars, higher than that on any other moon and, remarkably, even higher than that of the terrestrial planets Mars and Earth. The atmospheric composition is primarily nitrogen, an important way in which Titan’s atmosphere resembles Earth’s.

Also detected in Titan’s atmosphere were carbon monoxide (CO), hydrocarbons (compounds of hydrogen and carbon) such as methane (CH<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), and propane (C<sub>3</sub>H<sub>8</sub>), and nitrogen compounds such as hydrogen cyanide (HCN), cyanogen (C<sub>2</sub>N<sub>2</sub>), and cyanoacetylene (HC<sub>3</sub>N). Their presence indicates an active chemistry in which sunlight interacts with atmospheric nitrogen and methane to create a rich mix of organic molecules. There are also multiple layers of hydrocarbon haze and clouds in the atmosphere, as illustrated in

Figure 12.12.

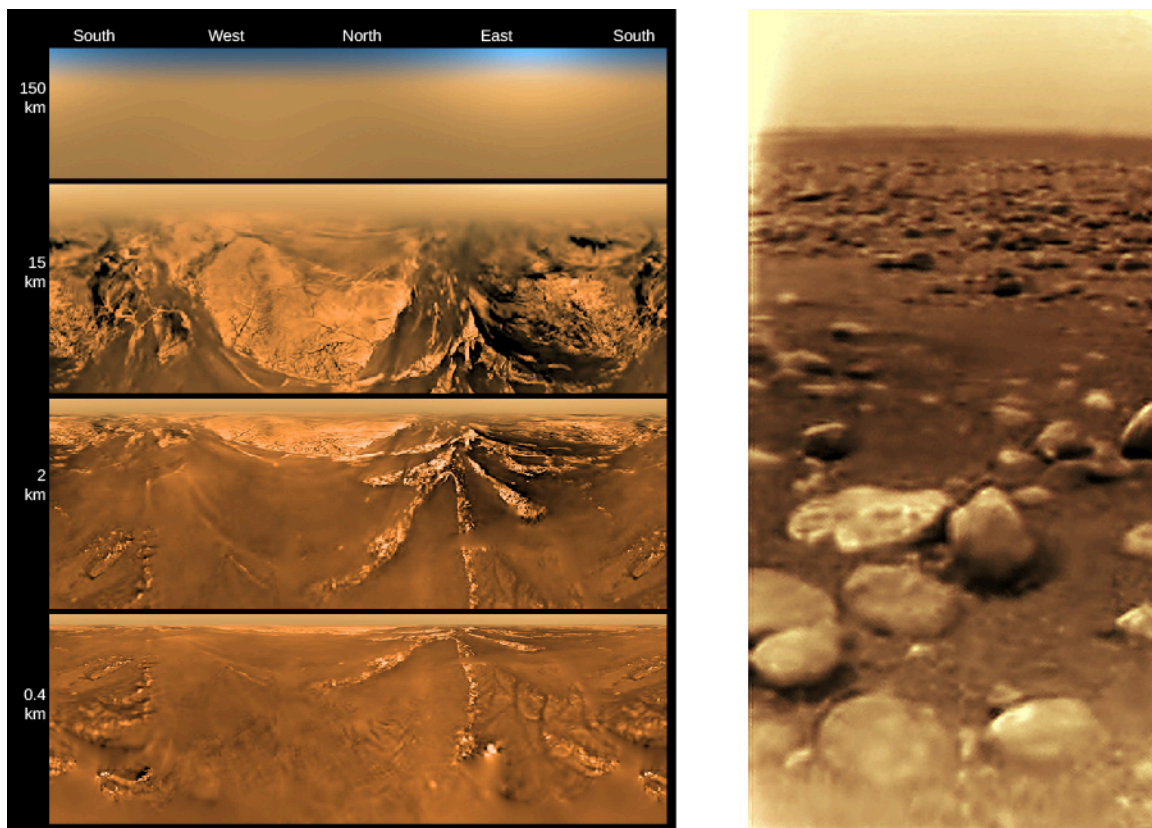


**Figure 12.12 Structure of Titan's Atmosphere.** Some characteristics of Titan's atmosphere resemble those of Earth's atmosphere, although it is much colder than our planet. The red line indicates the temperature of Titan's atmosphere at different altitudes.

These Voyager discoveries motivated a much more ambitious exploration program using the NASA Cassini Saturn orbiter and a probe to land on Titan called Huygens, built by the European Space Agency. The orbiter, which included several cameras, spectrometers, and a radar imaging system, made dozens of close flybys of Titan between 2004 and 2015, each yielding radar and infrared images of portions of the surface (see [Exploring the Outer Planets](#)). The Huygens probe successfully descended by parachute through the atmosphere, photographing the surface from below the clouds, and landing on January 14, 2005. This was the first (and so far the only) spacecraft landing on a moon in the outer solar system.

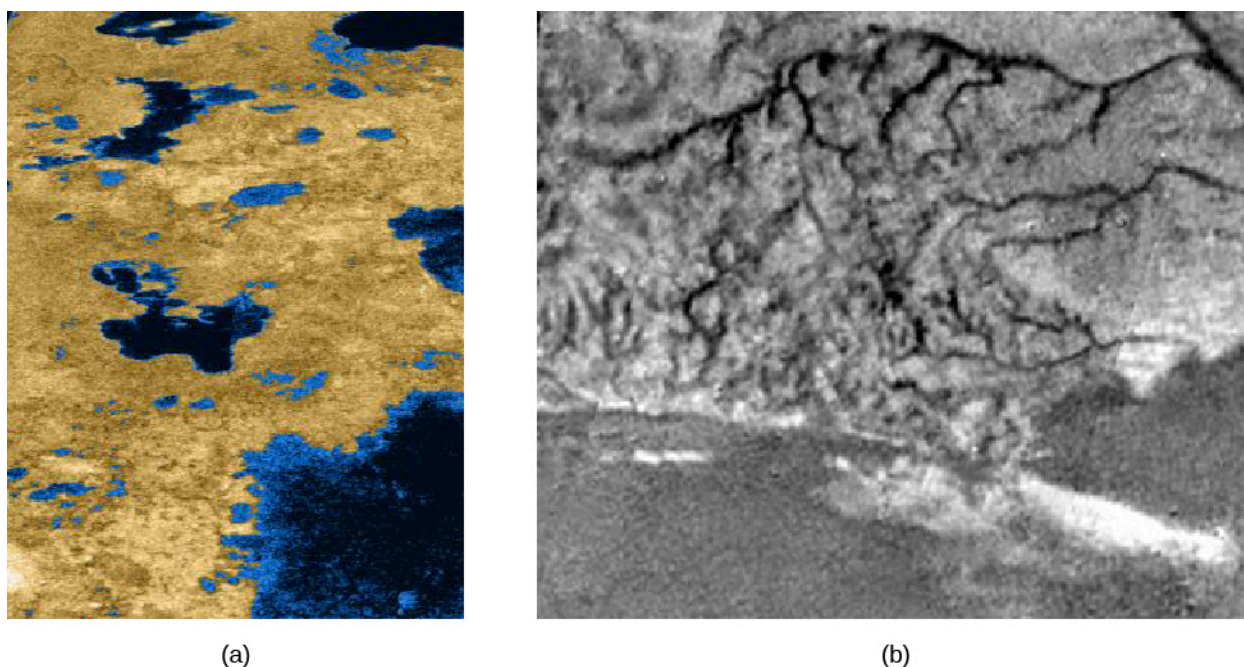
At the end of its parachute descent, the 319-kilogram Huygens probe safely touched down, slid a short distance, and began sending data back to Earth, including photos and analyses of the atmosphere. It appeared to have landed on a flat, boulder-strewn plain, but both the surface and the boulders were composed of water ice, which is as hard as rock at the temperature of Titan (see [Figure 12.13](#)).

The photos taken during descent showed a variety of features, including drainage channels, suggesting that Huygens had landed on the shore of an ancient hydrocarbon lake. The sky was deep orange, and the brightness of the Sun was a thousand times less than sunlight on Earth (but still more than a hundred times brighter than under the full moon on Earth). Titan's surface temperature was 94 K (−179 °C). The warmer spacecraft heated enough of the ice where it landed for its instruments to measure released hydrocarbon gas. Measurements on the surface continued for more than an hour before the probe succumbed to the frigid temperature.



**Figure 12.13 Views of the Surface of Titan.** The left image shows the views of Titan from the descent camera, in a flattened projection, at different altitudes. The right image, taken after landing, shows a boulder-strewn surface illuminated by faint reddish sunlight. The boulders are composed of water ice. (credit left: modification of work by ESA/NASA/JPL/University of Arizona; credit right: modification of work by ESA/NASA/JPL/University of Arizona; processed by Andrey Pivovarov)

Radar and infrared imaging of Titan from the Cassini orbiter gradually built up a picture of a remarkably active surface on this moon, complex and geologically young ([Figure 12.14](#)). There are large methane lakes near the polar regions that interact with the methane in the atmosphere, much as Earth's water oceans interact with the water vapor in our atmosphere. The presence of many erosional features indicates that atmospheric methane can condense and fall as rain, then flow down valleys to the big lakes. Thus, Titan has a low-temperature equivalent of the water cycle on Earth, with liquid on the surface that evaporates, forms clouds, and then condenses to fall as rain—but on Titan the liquid is a combination of methane, ethane, and a trace of other hydrocarbons. It is a weirdly familiar and yet utterly alien landscape.



**Figure 12.14 Titan's Lakes.** (a) This Cassini image from a September 2006 flyby shows the liquid lakes on Titan. Their composition is most likely a combination of methane and ethane. (Since this is a radar image, the colors are artificially added. The dark blue areas are the smooth surfaces of the liquid lakes, and yellow is the rougher solid terrain around them.) (b) This mosaic of Titan's surface from the Cassini-Huygens mission shows in detail a high ridge area and many narrow, sinuous erosion channels that appear to be part of a widespread network of "rivers" carved by flowing hydrocarbons. (credit a: modification of work by NASA/JPL-Caltech/USGS; credit b; modification of work by NASA/JPL/ESA/University of Arizona)

These discoveries raise the question of whether there could be life on Titan. Hydrocarbons are fundamental for the formation of the large carbon molecules that are essential to life on our planet. However, the temperature on Titan is far too low for liquid water or for many of the chemical processes that are essential to life as we know it. There remains, though, an intriguing possibility that Titan might have developed a different form of low-temperature carbon-based life that could operate with liquid hydrocarbons playing the role of water. The discovery of such "life as we don't know it" could be even more exciting than finding life like ours on Mars. If such a truly alien life is present on Titan, its existence would greatly expand our understanding of the nature of life and of habitable environments.

NASA has selected a new mission to Titan for launch in 2027. Called *Dragonfly*, this mission is a drone that will fly in Titan's atmosphere, with emphasis on study of pre-biotic chemistry. Other future proposed missions include a balloon operating in the atmosphere and a "boat" floating in one of the Titan lakes.

#### LINK TO LEARNING



The Cassini mission scientists and the visual presentation specialists at NASA's Jet Propulsion Laboratory have put together some nice films from the images taken by Cassini and Huygens. See, for example, the [Titan approach](https://openstax.org/l/30Titan) (<https://openstax.org/l/30Titan>) and the [flyover](https://openstax.org/l/30Titan2) (<https://openstax.org/l/30Titan2>) of the Northern lakes district.

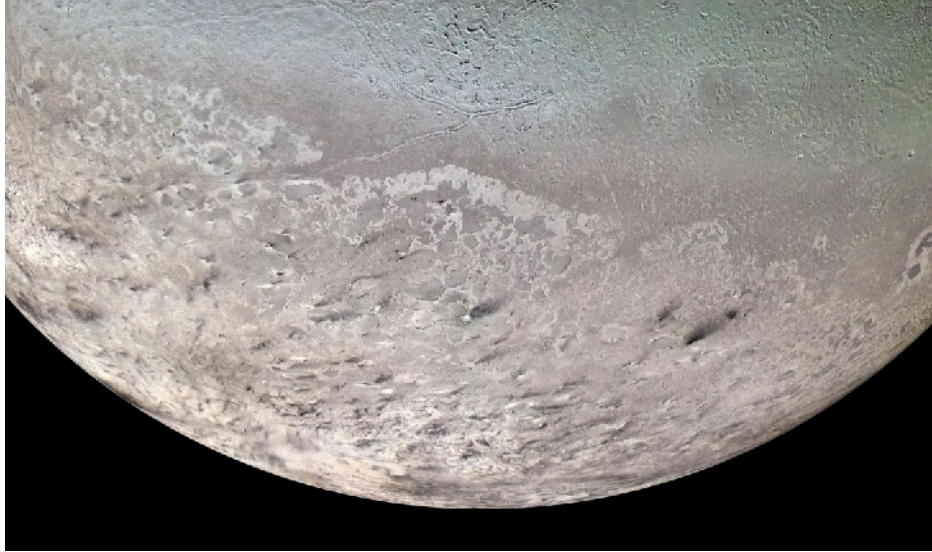
### Triton and Its Volcanoes

Neptune's largest moon Triton (don't get its name confused with Titan) has a diameter of 2720 kilometers and a density of  $2.1 \text{ g/cm}^3$ , indicating that it's probably composed of about 75% rock mixed with 25% water ice. Measurements indicate that Triton's surface has the coldest temperature of any of the worlds our robot representatives have visited. Because its reflectivity is so high (about 80%), Triton reflects most of the solar

energy that falls on it, resulting in a surface temperature between 35 and 40 K.

The surface material of Triton is made of frozen water, nitrogen, methane, and carbon monoxide. Methane and nitrogen exist as gas in most of the solar system, but they are frozen at Triton's temperatures. Only a small quantity of nitrogen vapor persists to form an atmosphere. Although the surface pressure of this atmosphere is only 16 millionths of a bar, this is sufficient to support thin haze or cloud layers.

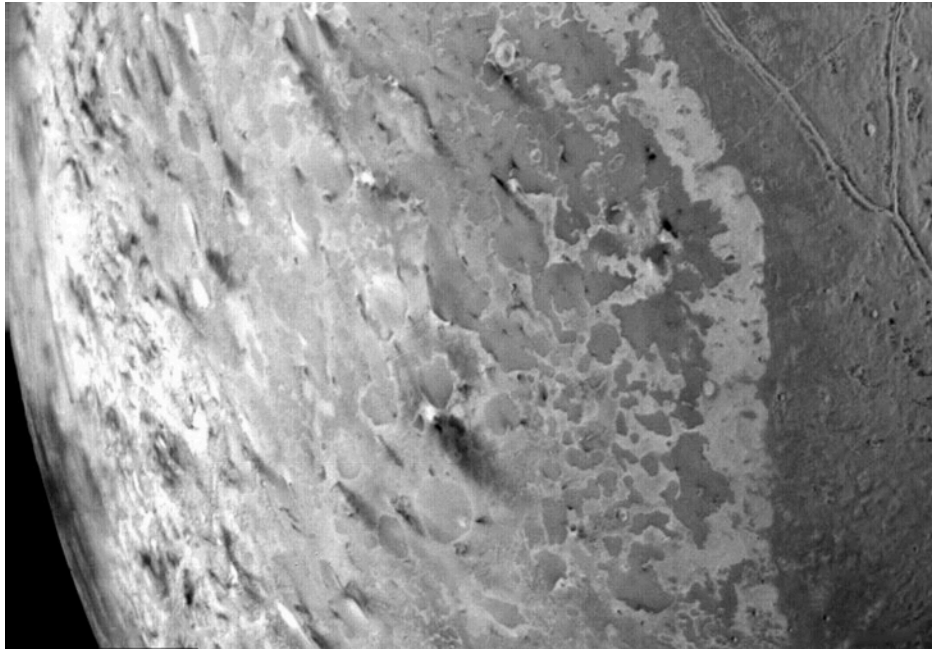
Triton's surface, like that of many other moons in the outer solar system, reveals a long history of geological evolution ([Figure 12.15](#)). Although some impact craters are found, many regions have been flooded fairly recently by the local version of "lava" (perhaps water or water-ammonia mixtures). There are also mysterious regions of jumbled or mountainous terrain.



**Figure 12.15 Neptune's Moon Triton.** This mosaic of Voyager 2 images of Triton shows a wide range of surface features. The pinkish area at the bottom is Triton's large southern polar cap. The south pole of Triton faces the Sun here, and the slight heating effect is driving some of the material northward, where it is colder. (credit: modification of work by NASA/JPL/USGS)

The Voyager flyby of Triton took place at a time when the moon's southern pole was tipped toward the Sun, allowing this part of the surface to enjoy a period of relative warmth. (Remember that "warm" on Triton is still outrageously colder than anything we experience on Earth.) A polar cap covers much of Triton's southern hemisphere, apparently evaporating along the northern edge. This polar cap may consist of frozen nitrogen that was deposited during the previous winter.

Remarkably, the Voyager images showed that the evaporation of Triton's polar cap generates geysers or volcanic plumes of nitrogen gas (see [Figure 12.16](#)). (Fountains of such gas rose about 10 kilometers high, visible in the thin atmosphere because dust from the surface rose with them and colored them dark.) These plumes differ from the volcanic plumes of Io in their composition and also in that they derive their energy from sunlight warming the surface rather than from internal heat.



**Figure 12.16 Triton's Geysers.** This close-up view shows some of the geysers on Neptune's moon Triton, with the long trains of dust pointing to the lower right in this picture. (credit: modification of work by NASA/JPL)

## 12.4 Pluto and Charon

### Learning Objectives

By the end of this section, you will be able to:

- Compare the orbital characteristics of Pluto with those of the planets
- Describe information about Pluto's surface deduced from the New Horizons images
- Note some distinguishing characteristics of Pluto's large moon Charon

Pluto is not a moon, but we discuss it here because its size and composition are similar to many moons in the outer solar system. Our understanding of Pluto (and its large moon Charon) have changed dramatically as a result of the New Horizons flyby in 2015.

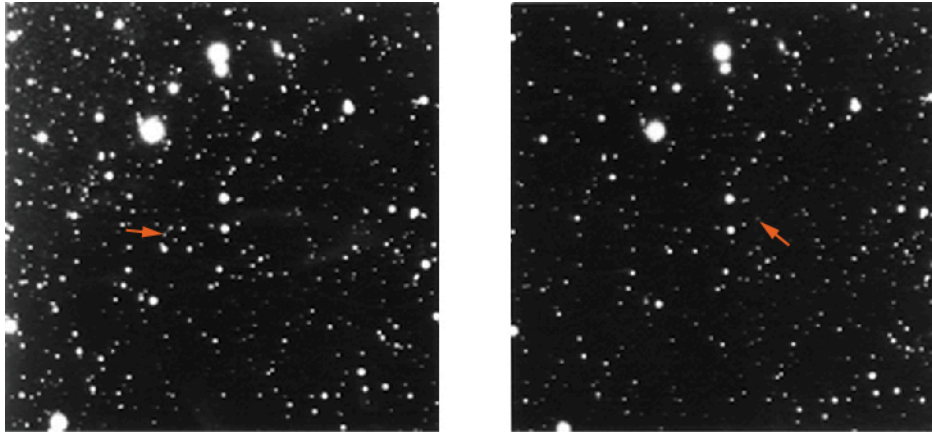
### Is Pluto a Planet?

Pluto was discovered through a careful, systematic search, unlike Neptune, whose position was calculated from gravitational theory. Nevertheless, the history of the search for Pluto began with indications that Uranus had slight departures from its predicted orbit, departures that could be due to the gravitation of an undiscovered "Planet X." Early in the twentieth century, several astronomers, most notably Percival Lowell, then at the peak of his fame as an advocate of intelligent life on Mars, became interested in searching for this ninth planet.

Lowell and his contemporaries based their calculations primarily on tiny unexplained irregularities in the motion of Uranus. Lowell's computations indicated two possible locations for a perturbing Planet X; the more likely of the two was in the constellation Gemini. He predicted a mass for the planet intermediate between the masses of Earth and Neptune (his calculations gave about 6 Earth masses). Other astronomers, however, obtained other solutions from the tiny orbital irregularities, even including one model that indicated two planets beyond Neptune.

At his Arizona observatory, Lowell searched without success for the unknown planet from 1906 until his death in 1916, and the search was not renewed until 1929. In February 1930, a young observing assistant named Clyde Tombaugh (see the [Clyde Tombaugh: From the Farm to Fame](#) feature box), comparing photographs he made on January 23 and 29 of that year, found a faint object whose motion appeared to be about right for a

planet far beyond the orbit of Neptune ([Figure 12.17](#)). The new planet was named for Pluto, the Roman god of the underworld, who dwelt in remote darkness, just like the new planet. The choice of this name, among hundreds suggested, was helped by the fact that the first two letters were Percival Lowell's initials.



**Figure 12.17 Pluto's Motion.** Portions of the two photographs by which Clyde Tombaugh discovered Pluto in 1930. The left one was taken on January 23 and the right on January 29. Note that Pluto, indicated by an arrow, has moved among the stars during those six nights. If we hadn't put an arrow next to it, though, you probably would never have spotted the dot that moved. (credit: modification of work by the Lowell Observatory Archives)

Although the discovery of Pluto appeared initially to be a vindication of gravitational theory similar to the earlier triumph of Adams and Le Verrier in predicting the position of Neptune, we now know that Lowell's calculations were wrong. When its mass and size were finally measured, it was found that Pluto could not possibly have exerted any measurable pull on either Uranus or Neptune. Astronomers are now convinced that the reported small anomalies in the motions of Uranus are not, and never were, real.

From the time of its discovery, it was clear that Pluto was not a giant like the other four outer solar system planets. For a long time, it was thought that the mass of Pluto was similar to that of Earth, so that it was classed as a fifth terrestrial planet, somehow misplaced in the far outer reaches of the solar system. There were other anomalies, however, as Pluto's orbit was more eccentric and inclined to the plane of our solar system than that of any other planet. Only after the discovery of its moon Charon in 1978 could the mass of Pluto be measured, and it turned out to be far less than the mass of Earth.

In addition to Charon, Pluto has four much smaller moons. Subsequent observations of Charon showed that this moon is in a retrograde orbit and has a diameter of about 1200 kilometers, more than half the size of Pluto itself ([Figure 12.18](#)). This makes Charon the moon whose size is the largest fraction of its parent planet. We could even think of Pluto and Charon as a double world. Seen from Pluto, Charon would be as large as eight full moons on Earth.



**Figure 12.18 Comparison of the Sizes of Pluto and Its Moon Charon with Earth.** This graphic vividly shows how tiny Pluto is relative to a terrestrial planet like Earth. That is the primary justification for putting Pluto in the class of dwarf planets rather than terrestrial planets. (credit: modification of work by NASA)

To many astronomers, Pluto seemed like the odd cousin that everyone hopes will not show up at the next family reunion. Neither its path around the Sun nor its size resembles either the giant planets or the terrestrial planets. In the 1990s, astronomers began to discover additional small objects in the far outer solar system, showing that Pluto was not unique. We will discuss these trans-neptunian objects later with other small bodies, in the chapter on [Comets and Asteroids: Debris of the Solar System](#). One of them (called Eris) is nearly the same size as Pluto, and another (Makemake) is substantially smaller. It became clear to astronomers that Pluto was so different from the other planets that it needed a new classification. Therefore, it was called a *dwarf planet*, meaning a planet much smaller than the terrestrial planets. We now know of many small objects in the vicinity of Pluto and we have classified several as dwarf planets.

A similar history was associated with the discovery of the asteroids. When the first asteroid (Ceres) was discovered at the beginning of the nineteenth century, it was hailed as a new planet. In the following years, however, other objects were found with similar orbits to Ceres. Astronomers decided that these should not all be considered planets, so they invented a new class of objects, called minor planets or asteroids. Today, Ceres is also called a dwarf planet. Both minor planets and dwarf planets are part of a whole belt or zones of similar objects (as we will discuss in [Comets and Asteroids: Debris of the Solar System](#)).

So, is Pluto a planet? Our answer is yes, but it is a *dwarf planet*, clearly not in the same league with the eight major planets (four giants and four terrestrials). While some people were upset when Pluto was reclassified, we might point out that a dwarf tree is still a type of tree and (as we shall see) a dwarf galaxy is still a type of galaxy.

## VOYAGERS IN ASTRONOMY



### Clyde Tombaugh: From the Farm to Fame

Clyde Tombaugh discovered Pluto when he was 24 years old, and his position as staff assistant at the Lowell Observatory was his first paying job. Tombaugh had been born on a farm in Illinois, but when he was 16, his family moved to Kansas. There, with his uncle's encouragement, he observed the sky through a telescope

the family had ordered from the Sears catalog. Tombaugh later constructed a larger telescope on his own and devoted his nights (when he wasn't too tired from farm work) to making detailed sketches of the planets ([Figure 12.19](#)).



(a)



(b)

**Figure 12.19 Clyde Tombaugh (1906–1997).** (a) Tombaugh is pictured on his family farm in 1928 with a 9-inch telescope he built. (b) Here Tombaugh is looking through an eyepiece at the Lowell Observatory. (credit b: modification of work by NASA)

In 1928, after a hailstorm ruined the crop, Tombaugh decided he needed a job to help support his family. Although he had only a high school education, he thought of becoming a telescope builder. He sent his planet sketches to the Lowell Observatory, seeking advice about whether such a career choice was realistic. By a wonderful twist of fate, his query arrived just when the Lowell astronomers realized that a renewed search for a ninth planet would require a very patient and dedicated observer.

The large photographic plates (pieces of glass with photographic emulsion on them) that Tombaugh was hired to take at night and search during the day contained an average of about 160,000 star images each. How to find Pluto among them? The technique involved taking two photographs about a week apart. During that week, a planet would move a tiny bit, while the stars remained in the same place relative to each other. A new instrument called a “blink comparator” could quickly alternate the two images in an eyepiece. The stars, being in the same position on the two plates, would not appear to change as the two images were “blinked.” But a moving object would appear to wiggle back and forth as the plates were alternated.

After examining more than 2 million stars (and many false alarms), Tombaugh found his planet on February 18, 1930. The astronomers at the observatory checked his results carefully, and the find was announced on March 13, the 149th anniversary of the discovery of Uranus. Congratulations and requests for interviews poured in from around the world. Visitors descended on the observatory in scores, wanting to see the place where the first new planet in almost a century had been discovered, as well as the person who had discovered it.

In 1932, Tombaugh took leave from Lowell, where he had continued to search and blink, to get a college degree. Eventually, he received a master's degree in astronomy and taught navigation for the Navy during World War II. In 1955, after working to develop a rocket-tracking telescope, he became a professor at New Mexico State University, where he helped found the astronomy department. He died in 1997; some of his ashes were placed inside the New Horizons spacecraft to Pluto.

## LINK TO LEARNING

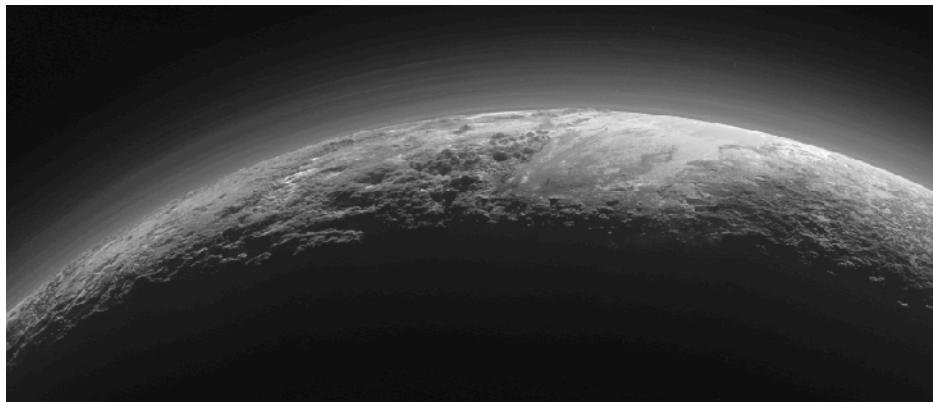


Here is a [touching video \(https://openstax.org/l/30Tbaugh\)](https://openstax.org/l/30Tbaugh) about Tombaugh's life as described by his children.

## The Nature of Pluto

Almost everything we know about Pluto and its moons comes from the New Horizons spacecraft, which flew by in 2015 before traveling on into the outermost parts of the planetary system. Using data from the New Horizons probe, astronomers have measured the diameter of Pluto as 2370 kilometers, only 60 percent as large as our Moon. From the diameter and mass, we find a density of  $1.9 \text{ g/cm}^3$ , suggesting that Pluto is a mixture of rocky materials and water ice in about the same proportions as many outer-planet moons.

Parts of Pluto's surface are highly reflective, and its spectrum demonstrates the presence on its surface of frozen methane, carbon monoxide, and nitrogen. The maximum surface temperature ranges from about 50 K when Pluto is farthest from the Sun to 60 K when it is closest. Even this small difference is enough to cause a partial sublimation (going from solid to gas) of the methane and nitrogen ice. This generates an atmosphere when Pluto is close to the Sun, and it freezes out when Pluto is farther away. Observations of distant stars seen through this thin atmosphere indicate that the surface pressure is about a ten-thousandth of Earth's. Because Pluto is a few degrees warmer than Triton, its atmospheric pressure is about ten times greater. This atmosphere contains several distinct haze layers, presumably caused by photochemical reactions, like those in Titan's atmosphere ([Figure 12.20](#)).



**Figure 12.20 Haze Layers in the Atmosphere of Pluto.** This is one of the highest-resolution photos of Pluto, taken by the New Horizons spacecraft 15 minutes after its closest approach. It shows 12 layers of haze. Note also the range of mountains with heights up to 3500 meters. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)

Reaching Pluto with a spacecraft was a major challenge, especially in an era when reduced NASA budgets could not support large, expensive missions like Galileo and Cassini. Yet like Galileo and Cassini, a Pluto mission would require a nuclear electric system that used the heat from plutonium to generate the energy to power the instruments and keep them operating far from the warmth of the Sun. NASA made available one of the last of its nuclear generators for such a mission. Assuming an affordable but highly capable spacecraft could be built, there was still the problem of getting to Pluto, nearly 5 billion kilometers from Earth, without waiting decades. The answer was to use Jupiter's gravity to slingshot the spacecraft toward Pluto.

The 2006 launch of New Horizons started the mission with a high speed, and the Jupiter flyby just a year later gave it the required additional boost. The New Horizons spacecraft arrived at Pluto in July 2015, traveling at a relative speed of 14 kilometers per second (or about 50,000 kilometers per hour). With this high speed, the entire flyby sequence was compressed into just one day. Most of the data recorded near closest approach

could not be transmitted to Earth until many months later, but when it finally arrived, astronomers were rewarded with a treasure trove of images and data.

### Geology of Pluto

Pluto is not the geologically dead world that many anticipated for such a small object—far from it. The division of the surface into areas with different composition and surface texture is apparent in the global color photo shown in [Figure 12.21](#). The reddish color is enhanced in this image to bring out differences in color more clearly. The darker parts of the surface are cratered, but adjacent to them is a nearly featureless light area in the lower right quadrant of this image. This is a huge ice-filled depression called the Sputnik Plains, named for the first artificial Earth satellite. The absence of impact craters suggests a surface no more than 10 million years old. The dark areas show the colors of photochemical haze or smog similar to that in the atmosphere of Titan. The dark material that is staining these old surfaces could come from Pluto’s atmospheric haze or from chemical reactions taking place at the surface due to the action of sunlight.



**Figure 12.21 Global Color Image of Pluto.** This New Horizons image clearly shows the variety of terrains on Pluto. The dark area in the lower left is covered with impact craters, while the large light area in the center and lower right is a flat basin devoid of craters. The colors you see are somewhat enhanced to bring out subtle differences. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)

[Figure 12.22](#) shows some of the remarkable variety of surface features New Horizons revealed. we are finding on Pluto. Toward the right on this image, we see the shoreline of the Sputnik Plains, showing evidence of relatively recent geological activity. The nitrogen and carbon monoxide ice that fills the Sputnik depression shows cells or polygons with an average width of more than 30 kilometers, caused by slow convection in the ice.<sup>2</sup>

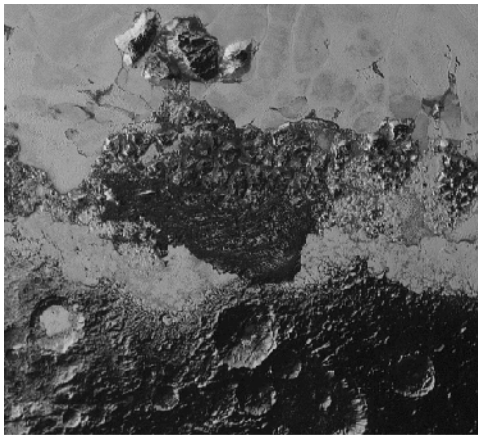
<sup>2</sup> In the process of convection, warmer material rises and colder material sinks, transferring energy. You are probably more familiar with convection in warm fluids, like the cells you see when you are heating some kinds of soup, but it can also happen (very slowly) in colder substances.



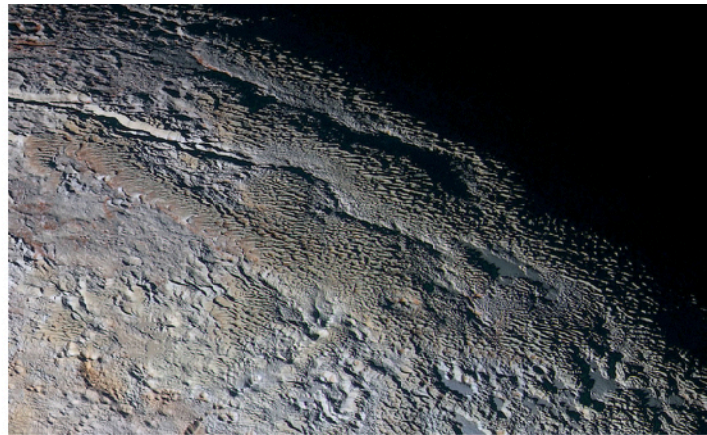
**Figure 12.22 Diversity of Terrain on Pluto.** This enhanced color view of a strip of Pluto's surface about 80 kilometers long shows a variety of different surface features. From left to right, we first cross a region of "badlands" with some craters showing, and then move across a wide range of mountains made of water ice and coated with the redder material we saw in the previous image. Then, at right, we arrive at the "shoreline" of the great sea of frozen nitrogen that the mission scientists have named the "Sputnik Plains." This nitrogen sea is divided into mysterious cells or segments that are many kilometers across. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)

[Figure 12.23](#) shows another view of the boundary between different types of geology. The width of this image is 250 kilometers, and it shows dark, ancient, heavily cratered terrain; dark, uncratered terrain with a hilly surface; smooth, geologically young terrain; and a small cluster of mountains more than 3000 meters high. In the best images, the light areas of nitrogen ice seem to have flowed much like glaciers on Earth, covering some of the older terrain underneath them.

The isolated mountains in the midst of the smooth nitrogen plains are probably also made of water ice, which is very hard at the temperatures on Pluto and can float on frozen nitrogen. Additional mountains, and some hilly terrain that reminded the mission scientists of snakeskin, are visible in part (b) of [Figure 12.23](#).



(a)

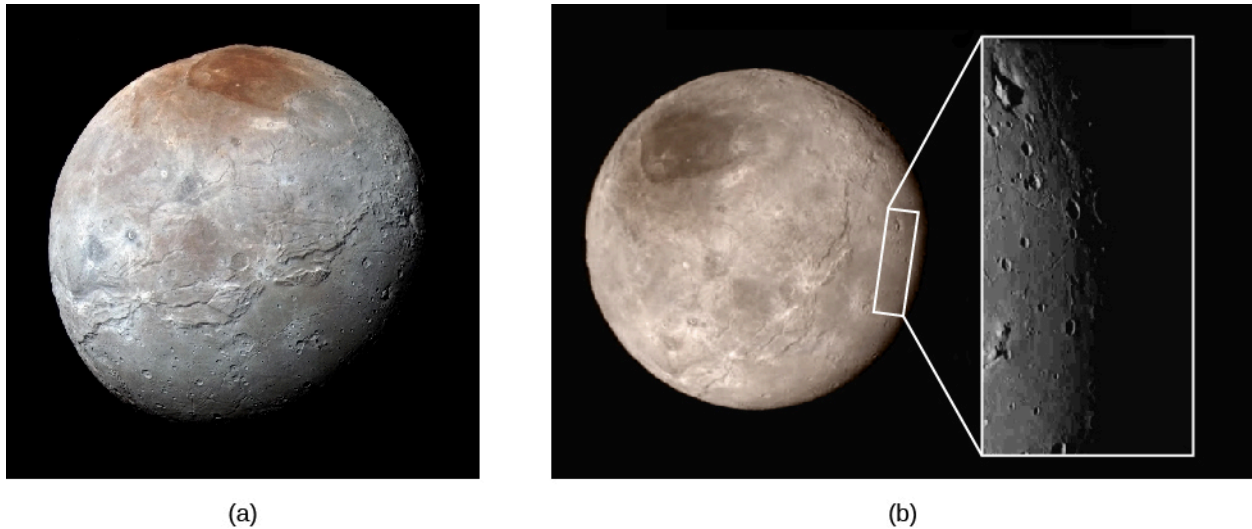


(b)

**Figure 12.23 Diversity of Terrains on Pluto.** (a) In this photo, about 250 kilometers across, we can see many different kinds of terrain. At the bottom are older, cratered highlands; a V-shaped region of hills without cratering points toward the bottom of the image. Surrounding the V-shaped dark region is the smooth, brighter frozen nitrogen plain, acting as glaciers on Earth do. Some isolated mountains, made of frozen water ice, are floating in the nitrogen near the top of the picture. (b) This scene is about 390 kilometers across. The rounded mountains, quite different from those we know on Earth, are named Tartarus Dorsa. The patterns, made of repeating ridges with the more reddish terrain between them, are not yet understood. (credit a, b: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)

### A Quick Look at Charon

To add to the mysteries of Pluto, we show in [Figure 12.24](#) one of the best New Horizons images of Pluto's large moon Charon. Recall from earlier that Charon is roughly half Pluto's size (its diameter is about the size of Texas). Charon keeps the same side toward Pluto, just as our Moon keeps the same side toward Earth. What is unique about the Pluto-Charon system, however, is that Pluto also keeps its same face toward Charon. Like two dancers embracing, these two constantly face each other as they spin across the celestial dance floor. Astronomers call this a double tidal lock.



**Figure 12.24 Pluto's Large Moon Charon.** (a) In this New Horizons image, the color has been enhanced to bring out the color of the moon's strange red polar cap. Charon has a diameter of 1214 kilometers, and the resolution of this image is 3 kilometers. (b) Here we see the moon from a slightly different angle, in true color. The inset shows an area about 390 kilometers from top to bottom. Near the top left is an intriguing feature—what appears to be a mountain in the middle of a depression or moat. (credit a, b: modification of work by NASA/JHUAPL/SwRI)

What New Horizons showed was another complex world. There are scattered craters in the lower part of the image, but much of the rest of the surface appears smooth. Crossing the center of the image is a belt of rough terrain, including what appear to be tectonic valleys, as if some forces had tried to split Charon apart. Topping off this strange image is a distinctly red polar cap, of unknown composition. Many features on Charon are not yet understood, including what appears to be a mountain in the midst of a low-elevation region.

## 12.5 Planetary Rings (and Enceladus)

### Learning Objectives

By the end of this section, you will be able to:

- › Describe the two theories of planetary ring formation
- › Compare the major rings of Saturn and explain the role of the moon Enceladus in the formation of the E ring
- › Explain how the rings of Uranus and Neptune differ in composition and appearance from the rings of Saturn
- › Describe how ring structure is affected by the presence of moons

In addition to their moons, all four of the giant planets have rings, with each ring system consisting of billions of small particles or “moonlets” orbiting close to their planet. Each of these rings displays a complicated structure that is related to interactions between the ring particles and the larger moons. However, the four ring systems are very different from each other in mass, structure, and composition, as outlined in [Table 12.2](#).

**Properties of the Ring Systems**

Planet	Outer Radius (km)	Outer Radius ( $R_{\text{planet}}$ )	Mass (kg)	Reflectivity (%)
Jupiter	128,000	1.8	$10^{10}(?)$	?
Saturn	140,000	2.3	$10^{19}$	60

**Table 12.2**

Planet	Outer Radius (km)	Outer Radius ( $R_{\text{planet}}$ )	Mass (kg)	Reflectivity (%)
Uranus	51,000	2.2	$10^{14}$	5
Neptune	63,000	2.5	$10^{12}$	5

Table 12.2

Saturn's large ring system is made up of icy particles spread out into several vast, flat rings containing a great deal of fine structure. The Uranus and Neptune ring systems, on the other hand, are nearly the reverse of Saturn's: they consist of dark particles confined to a few narrow rings with broad empty gaps in between. Jupiter's ring and at least one of Saturn's are merely transient dust bands, constantly renewed by dust grains eroded from small moons. In this section, we focus on the two most massive ring systems, those of Saturn and Uranus.

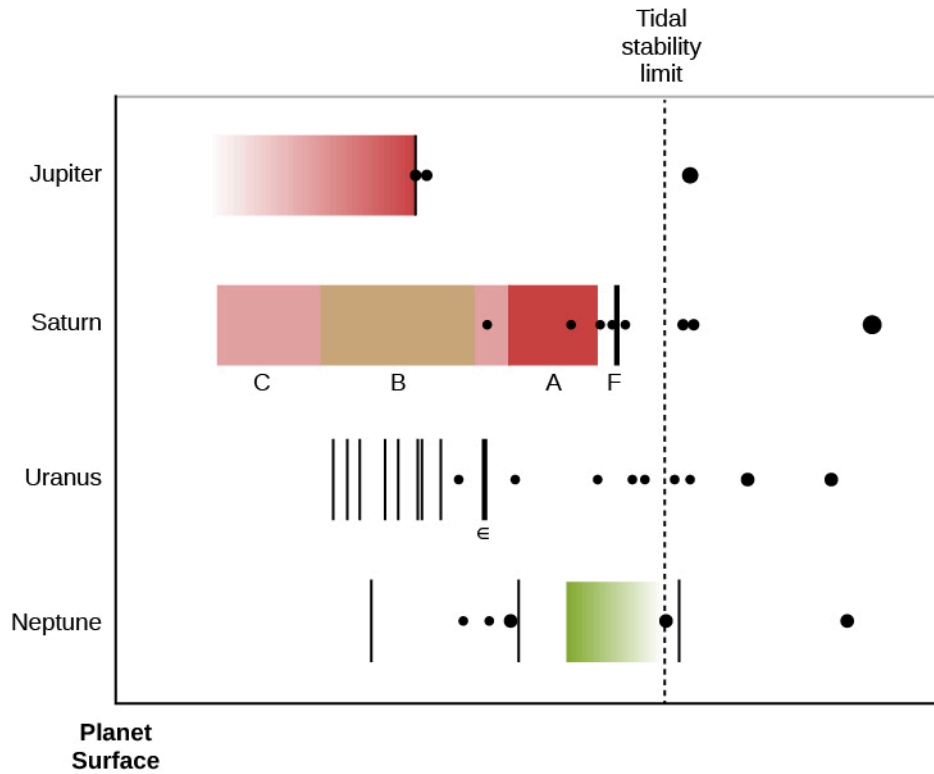
### What Causes Rings?

A ring is a collection of vast numbers of particles, each like a tiny moon obeying Kepler's laws as it follows its own orbit around the planet. Thus, the inner particles revolve faster than those farther out, and the ring as a whole does not rotate as a solid body. In fact, it is better not to think of a ring rotating at all, but rather to consider the revolution (or motion in orbit) of its individual moonlets.

If the ring particles were widely spaced, they would move independently, like separate moonlets. However, in the main rings of Saturn and Uranus the particles are close enough to exert mutual gravitational influence, and occasionally even to rub together or bounce off each other in low-speed collisions. Because of these interactions, we see phenomena such as waves that move across the rings—just the way water waves move over the surface of the ocean.

There are two basic ideas of how such rings come to be. First is the *breakup hypothesis*, which suggests that the rings are the remains of a shattered moon. A passing comet or asteroid might have collided with the moon, breaking it into pieces. Tidal forces then pulled the fragments apart, and they dispersed into a disk. The second hypothesis, which takes the reverse perspective, suggests that the rings are made of particles that were unable to come together to form a moon in the first place.

In either theory, the gravity of the planet plays an important role. Close to the planet (see [Figure 12.25](#)), tidal forces can tear bodies apart or inhibit loose particles from coming together. We do not know which explanation holds for any given ring, although many scientists have concluded that at least a few of the rings are relatively young and must therefore be the result of breakup.

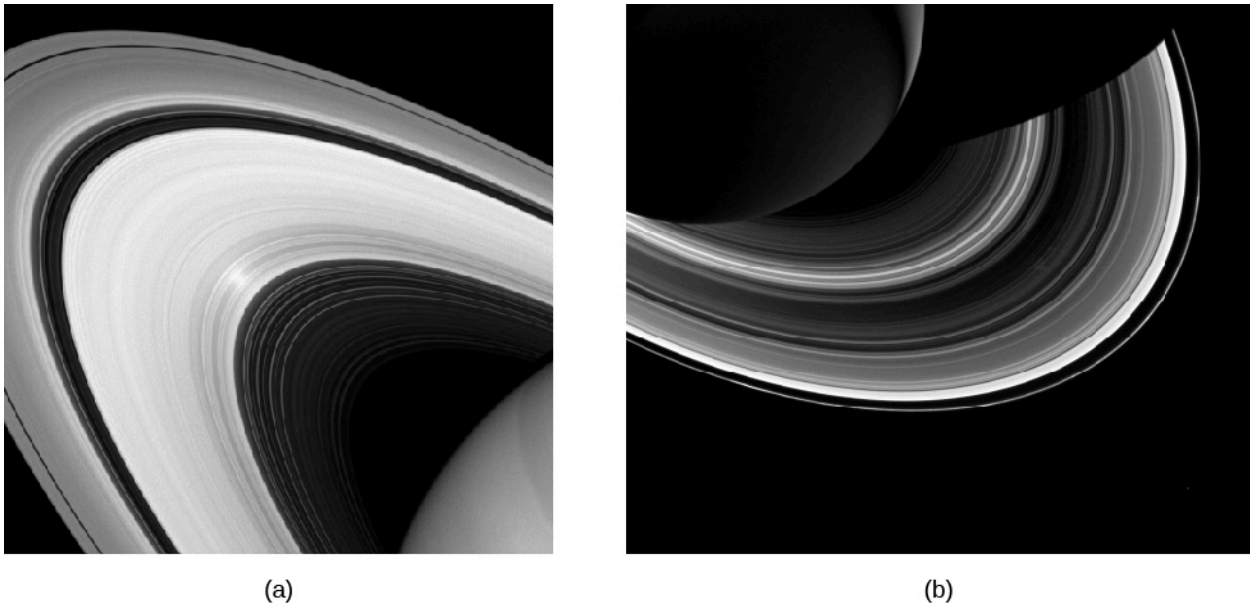


**Figure 12.25 Four Ring Systems.** This diagram shows the locations of the ring systems of the four giant planets. The left axis represents the planet's surface. The dotted vertical line is the limit inside which gravitational forces can break up moons (each planet's system is drawn to a different scale, so that this stability limit lines up for all four of them). The black dots are the inner moons of each planet on the same scale as its rings. Notice that only really small moons survive inside the stability limit.

### Rings of Saturn

Saturn's rings are one of the most beautiful sights in the solar system ([Figure 12.26](#)). From outer to inner, the three brightest rings are labeled with the extremely unromantic names of A, B, and C Rings. [Table 12.3](#) gives the dimensions of the rings in both kilometers and units of the radius of Saturn,  $R_{\text{Saturn}}$ . The B Ring is the brightest and has the most closely packed particles, whereas the A and C Rings are translucent.

The total mass of the B Ring, which is probably close to the mass of the entire ring system, is about equal to that of an icy moon 250 kilometers in diameter (suggesting that the ring could have originated in the breakup of such a moon). Between the A and B Rings is a wide gap named the Cassini Division after Gian Domenico Cassini, who first glimpsed it through a telescope in 1675 and whose name planetary scientists also gave to the Cassini spacecraft that explored the Saturn system.



**Figure 12.26 Saturn's Rings as Seen from Above and Below.** (a) The view from above is illuminated by direct sunlight. (b) The illumination seen from below is sunlight that has diffused through gaps in the rings. (credit a, b: modification of work by NASA/JPL-Caltech/Space Science Institute)

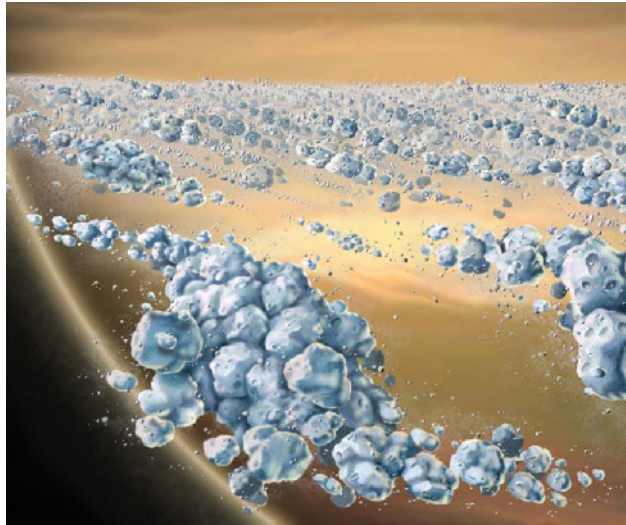
#### Selected Features in the Rings of Saturn

Ring Name <sup>3</sup>	Outer Edge ( $R_{\text{Saturn}}$ )	Outer Edge (km)	Width (km)
F	2.324	140,180	90
A	2.267	136,780	14,600
Cassini Division	2.025	122,170	4590
B	1.949	117,580	25,580
C	1.525	92,000	17,490

**Table 12.3**

Saturn's rings are very broad and very thin. The width of the main rings is 70,000 kilometers, yet their average thickness is only 20 meters. If we made a scale model of the rings out of paper, we would have to make them 1 kilometer across. On this scale, Saturn itself would loom as high as an 80-story building. The ring particles are composed primarily of water ice, and they range from grains the size of sand up to house-sized boulders. An insider's view of the rings would probably resemble a bright cloud of floating snowflakes and hailstones, with a few snowballs and larger objects, many of them loose aggregates of smaller particles ([Figure 12.27](#)).

<sup>3</sup> The ring letters are assigned in the order of their discovery.

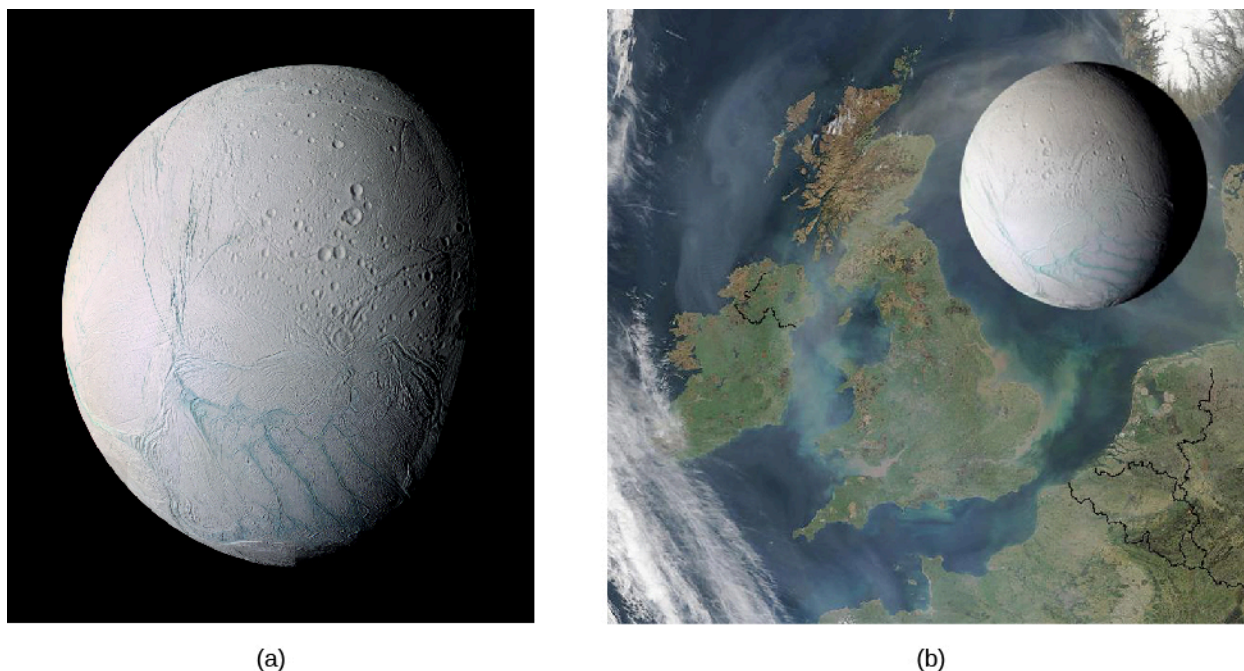


**Figure 12.27 Artist's Idealized Impression of the Rings of Saturn as Seen from the Inside.** Note that the rings are mostly made of pieces of water ice of different sizes. Toward the end of its mission, the Cassini spacecraft got nearer to the rings of Saturn, but it never got this close. (credit: modification of work by NASA/JPL/University of Colorado)

In addition to the broad A, B, and C Rings, Saturn has a handful of very narrow rings no more than 100 kilometers wide. The most substantial of these, which lies just outside the A Ring, is called the F Ring; its surprising appearance is discussed below. In general, Saturn's narrow rings resemble the rings of Uranus and Neptune.

There is also a very faint, tenuous ring, called the E Ring, associated with Saturn's small icy moon Enceladus. The particles in the E Ring are very small and composed of water ice. Since such a tenuous cloud of ice crystals will tend to dissipate, the ongoing existence of the E Ring strongly suggests that it is being continually replenished by a source at Enceladus. This icy moon is very small—only 500 kilometers in diameter—but the Voyager images showed that the craters on about half of its surface have been erased, indicating geological activity sometime in the past few million years. It was with great anticipation that the Cassini scientists maneuvered the spacecraft orbit to allow multiple close flybys of Enceladus starting in 2005.

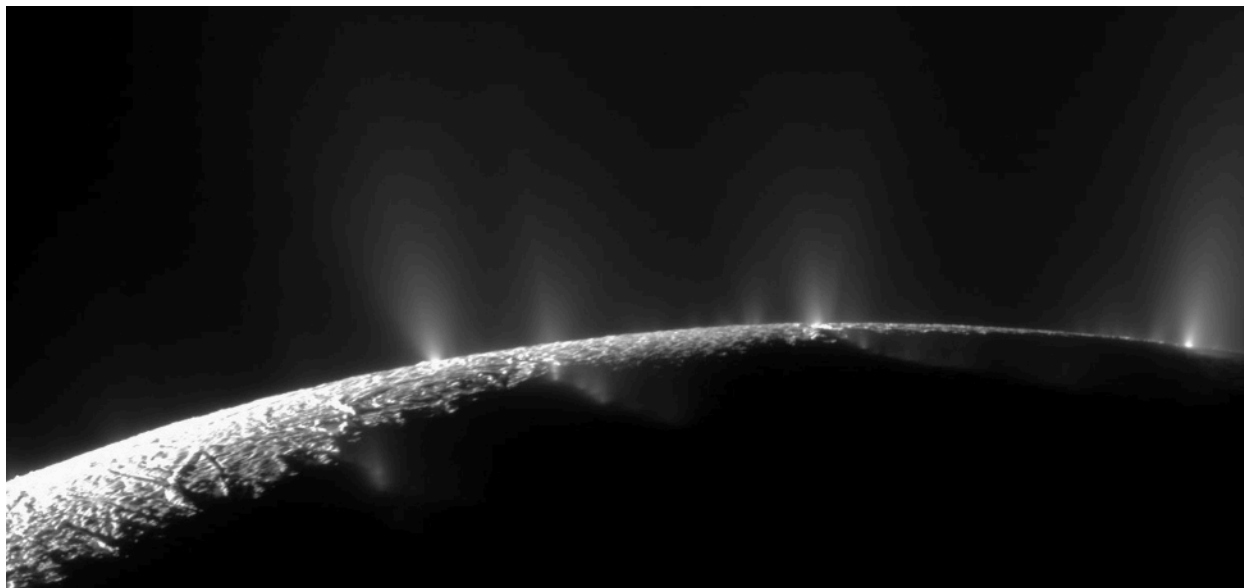
Those awaiting the Cassini flyby results were not disappointed. High-resolution images showed long, dark stripes of smooth ground near its south pole, which were soon nicknamed “tiger stripes” ([Figure 12.28](#)). Infrared measurements revealed that these tiger stripes are warmer than their surroundings. Best of all, dozens of cryovolcanic vents on the tiger stripes were seen to be erupting geysers of salty water and ice ([Figure 12.29](#)). Estimates suggested that 200 kilograms of material were shooting into space each second—not a lot, but enough for the spacecraft to sample.



**Figure 12.28 Enceladus.** (a) This image shows both smooth and cratered terrain on Saturn's moon, and also "tiger stripes" in the south polar region (lower part of image). These dark stripes (shown here in exaggerated color) have elevated temperatures and are the source of the many geysers discovered on Enceladus. They are about 130 kilometers long and 40 kilometers apart. (b) Here Enceladus is shown to scale with Great Britain and the coast of Western Europe, to emphasize that it is a small moon, only about 500 kilometers in diameter. (credit a, b: modification of work by NASA/JPL/Space Science Institute)

When Cassini was directed to fly into the plumes, it measured their composition and found them to be similar to material we see liberated from comets (see [Comets and Asteroids: Debris of the Solar System](#)). The vapor and ice plumes consisted mostly of water, but with trace amounts of nitrogen, ammonia, methane, and other hydrocarbons. Minerals found in the geysers in trace amounts included ordinary salt, meaning that the geyser plumes were high-pressure sprays of salt water.

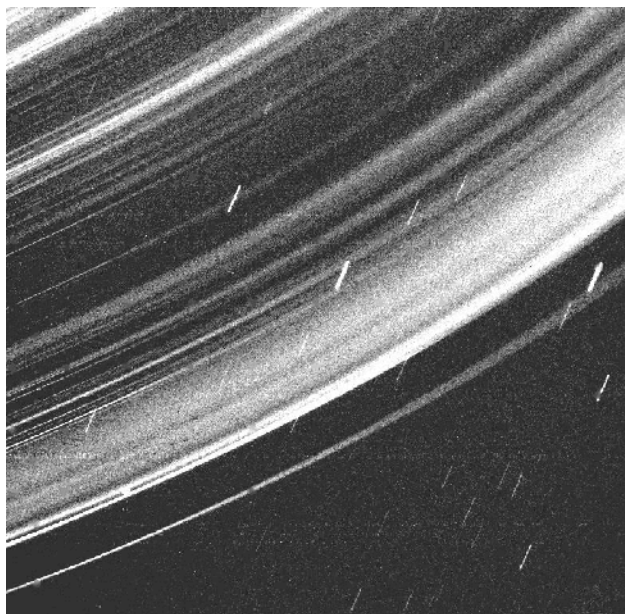
Based on the continuing study of Enceladus' bulk properties and the ongoing geysers, in 2015 the Cassini mission scientists tentatively identified a subsurface ocean of water feeding the geysers. These discoveries suggested that in spite of its small size, Enceladus should be added to the list of worlds that we would like to explore for possible life. Since its subsurface ocean is conveniently escaping into space, it might be much easier to sample than the ocean of Europa, which is deeply buried below its thick crust of ice.



**Figure 12.29 Geysers on Enceladus.** This Cassini image shows a number of water geysers on Saturn's small moon Enceladus, apparently salty water from a subsurface source escaping through cracks in the surface. You can see curved lines of geysers along the four "tiger stripes" on the surface. (credit: modification of work by NASA/JPL/Space Science Institute)

### Rings of Uranus and Neptune

Uranus' rings are narrow and black, making them almost invisible from Earth. The nine main rings were discovered in 1977 from observations made of a star as Uranus passed in front of it. We call such a passage of one astronomical object in front of another an *occultation*. During the 1977 occultation, astronomers expected the star's light to disappear as the planet moved across it. But in addition, the star dimmed briefly several times before Uranus reached it, as each narrow ring passed between the star and the telescope. Thus, the rings were mapped out in detail even though they could not be seen or photographed directly, like counting the number of cars in a train at night by watching the blinking of a light as the cars successively pass in front of it. When Voyager approached Uranus in 1986, it was able to study the rings at close range; the spacecraft also photographed two new rings ([Figure 12.30](#)).

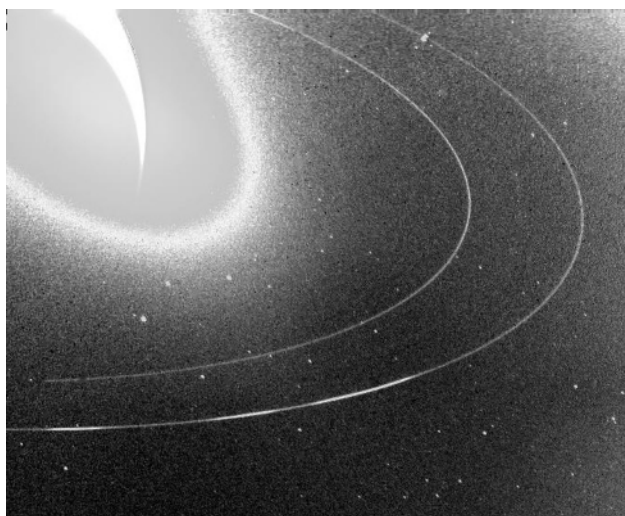


**Figure 12.30 Rings of Uranus.** The Voyager team had to expose this image for a long time to get a glimpse of Uranus' narrow dark rings. You can see the grainy structure of "noise" in the electronics of the camera in the picture background. (credit: modification of work by NASA/JPL)

The outermost and most massive of Uranus' rings is called the Epsilon Ring. It is only about 100 kilometers wide and probably no more than 100 meters thick (similar to the F Ring of Saturn). The Epsilon Ring encircles Uranus at a distance of 51,000 kilometers, about twice the radius of Uranus. This ring probably contains as much mass as all of Uranus' other ten rings combined; most of them are narrow ribbons less than 10 kilometers wide, just the reverse of the broad rings of Saturn.

The individual particles in the uranian rings are nearly as black as lumps of coal. While astronomers do not understand the composition of this material in detail, it seems to consist in large part of carbon and hydrocarbon compounds. Organic material of this sort is rather common in the outer solar system. Many of the asteroids and comets are also composed of dark, tarlike materials. In the case of Uranus, its ten small inner moons have a similar composition, suggesting that one or more moons might have broken up to make the rings.

Neptune's rings are generally similar to those of Uranus but even more tenuous (Figure 12.31). There are only four of them, and the particles are not uniformly distributed along their lengths. Because these rings are so difficult to investigate from Earth, it will probably be a long time before we understand them very well.



**Figure 12.31 Rings of Neptune.** This long exposure of Neptune's rings was photographed by Voyager 2. Note the two denser regions of the outer ring. (credit: modification of work by NASA/JPL)

### LINK TO LEARNING



Mark Showalter (of the SETI Institute) and his colleagues maintain the [NASA's Planetary Ring Node \(https://openstax.org/l/30NASArings\)](https://openstax.org/l/30NASArings) website. It is full of information about the rings and their interactions with moons; check out their press-release images of the Saturn ring system, for example. And Showalter gives an [entertaining illustrated talk \(https://openstax.org/l/30StrnRngs\)](https://openstax.org/l/30StrnRngs) about Saturn's ring and moon system.

### EXAMPLE 12.1

#### Resolution of Planetary Rings

Using the occultations of stars by the rings of Saturn, astronomers have been able to measure details in the ring structure to a resolution of 10 km. This is a much higher resolution than can be obtained in a conventional photo of the rings. Let's figure out what angular resolution (in arcsec) a space telescope in

Earth orbit would have to achieve to obtain equal resolution.

### Solution

To solve this problem, we use the “small-angle formula” to relate angular and linear diameters in the sky. For angles in the sky that are small, the formula is usually written as

$$\frac{\text{angular diameter}}{206,265 \text{ arcsec}} = \frac{\text{linear diameter}}{\text{distance}}$$

where angular diameter is expressed in arcsec. The distance of Saturn near opposition is about 9 AU =  $1.4 \times 10^9$  km. Substituting in the above formula and solving for the angular resolution, we get

$$\text{angular resolution} = \frac{206,265 \text{ arcsec} \times 10}{1.4 \times 10^9 \text{ km}}$$

which is about  $10^{-3}$  arcsec, or a milliarcsec. This is not possible for our telescopes to achieve. For comparison, the best resolution from either the Hubble Space Telescope or ground-based telescopes is about 0.1 arcsec, or 100 times worse than what we would need. This is why such occultation measurements are so useful for astronomers.

### Check Your Learning

How close to Saturn would a spacecraft have to be to make out detail in its rings as small as 20 km, if its camera has an angular resolution of 5 arcsec?

#### Answer:

Using our formula,

$$\frac{\text{angular diameter}}{206,265 \text{ arcsec}} = \frac{\text{linear diameter}}{\text{distance}}$$

we get

$$\frac{5 \text{ arcsec}}{206,265 \text{ arcsec}} = \frac{20 \text{ km}}{\text{distance}}$$

So, the distance is about 825,000 km.

## Interactions between Rings and Moons

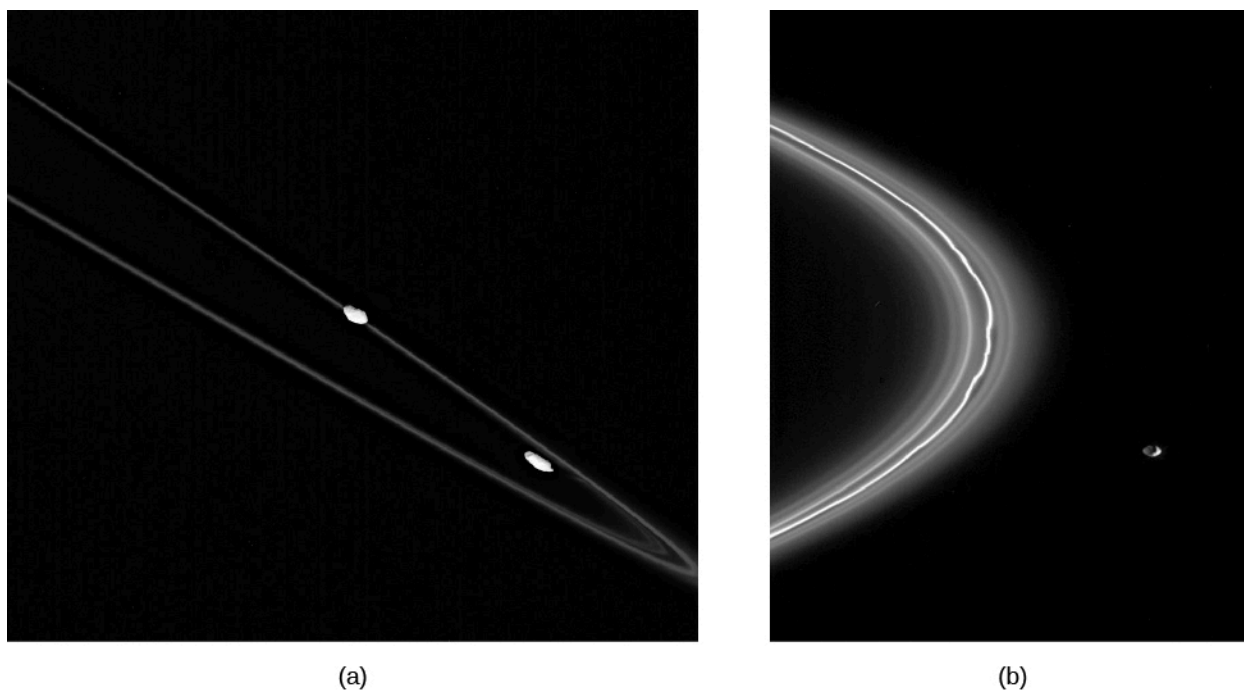
Much of our fascination with planetary rings is a result of their intricate structures, most of which owe their existence to the gravitational effect of moons, without which the rings would be flat and featureless. Indeed, it is becoming clear that without moons there would probably be no rings at all because, left to themselves, thin disks of small particles gradually spread and dissipate.

Most of the gaps in Saturn’s rings, and also the location of the outer edge of the A Ring, result from gravitational resonances with small inner moons. A **resonance** takes place when two objects have orbital periods that are exact ratios of each other, such as 1:2 or 2:3. For example, any particle in the gap at the inner side of the Cassini Division of Saturn’s rings would have a period equal to one-half that of Saturn’s moon Mimas. Such a particle would be nearest Mimas in the same part of its orbit every second revolution. The repeated gravitational tugs of Mimas, acting always in the same direction, would perturb it, forcing it into a new orbit outside the gap. In this way, the Cassini Division became depleted of ring material over long periods of time.

The Cassini mission revealed a great deal of fine structure in Saturn’s rings. Unlike the earlier Voyager flybys, Cassini was able to observe the rings for more than a decade, revealing a remarkable range of changes, on time scales from a few minutes to several years. Many of the features newly seen in Cassini data indicated the presence of condensations or small moons only a few tens of meters across imbedded in the rings. As each small moon moves, it produces waves in the surrounding ring material like the wake left by a moving ship. Even when the moon is too small to be resolved, its characteristic waves could be photographed by Cassini.

One of the most interesting rings of Saturn is the narrow F Ring, which contains several apparent ringlets within its 90-kilometer width. In places, the F Ring breaks up into two or three parallel strands that sometimes show bends or kinks. Most of the rings of Uranus and Neptune are also narrow ribbons like the F Ring of Saturn. Clearly, the gravity of some objects must be keeping the particles in these thin rings from spreading out.

As we have seen, the largest features in the rings of Saturn are produced by gravitational resonances with the inner moons, while much of the fine structure is caused by smaller embedded moons. In the case of Saturn's F Ring, close-up images revealed that it is bounded by the orbits of two moons, called Pandora and Prometheus (Figure 12.32). These two small moons (each about 100 kilometers in diameter) are referred to as *shepherd moons*, since their gravitation serves to "shepherd" the ring particles and keep them confined to a narrow ribbon. A similar situation applies to the Epsilon Ring of Uranus, which is shepherded by the moons Cordelia and Ophelia. These two shepherds, each about 50 kilometers in diameter, orbit about 2000 kilometers inside and outside the ring.



**Figure 12.32 Saturn's F Ring and Its Shepherd Moons.** (a) This Cassini image shows the narrow, complex F Ring of Saturn, with its two small shepherd moons Pandora (left) and Prometheus (right). (b) In this closer view, the shepherd moon Pandora (84 kilometers across) is seen next to the F ring, in which the moon is perturbing the main (brightest) strand of ring particles as it passes. You can see the dark side of Pandora on this image because it is being illuminated by the light reflected from Saturn. (credit a, b: modification of work by NASA/JPL/Space Science Institute)

#### LINK TO LEARNING



You can download a [movie \(https://openstax.org/l/30ShprdMns\)](https://openstax.org/l/30ShprdMns) showing the two shepherd moons on either side of Saturn's F ring.

Theoretical calculations suggest that the other narrow rings in the uranian and neptunian systems should also be controlled by shepherd moons, but none has been located. The calculated diameter for such shepherds (about 10 kilometers) was just at the limit of detectability for the Voyager cameras, so it is impossible to say whether they are present or not. (Given all the narrow rings we see, some scientists still hope to find another more satisfactory mechanism for keeping them confined.)

One of the outstanding problems with understanding the rings is determining their ages. Have the giant planets always had the ring systems we see today, or might these be a recent or transient addition to the solar system? In the case of the main rings of Saturn, their mass is about the same as that of the inner moon Mimas. Thus, they could have been formed by the break-up of a Mimas-sized moon, perhaps very early in solar system history, when there were many interplanetary projectiles left over from planet formation. It is harder to understand how such a catastrophic event could have taken place recently, when the solar system had become a more stable place.

## Key Terms

**resonance** an orbital condition in which one object is subject to periodic gravitational perturbations by another, most commonly arising when two objects orbiting a third have periods of revolution that are simple multiples or fractions of each other

**tidal heating** the heating of a planet or moon's interior by variable tidal forces caused by changing gravitational pull from a nearby planet or moon

## Summary

### [12.1 Ring and Moon Systems Introduced](#)

The four jovian planets are accompanied by impressive systems of moons and rings. Nearly 200 moons have been discovered in the outer solar system. Of the four ring systems, Saturn's is the largest and is composed primarily of water ice; in contrast, Uranus and Neptune have narrow rings of dark material, and Jupiter has a tenuous ring of dust.

### [12.2 The Galilean Moons of Jupiter](#)

Jupiter's largest moons are Ganymede and Callisto, both low-density objects that are composed of more than half water ice. Callisto has an ancient cratered surface, while Ganymede shows evidence of extensive tectonic and volcanic activity, persisting until perhaps a billion years ago. Io and Europa are denser and smaller, each about the size of our Moon. Io is the most volcanically active object in the solar system. Various lines of evidence indicate that Europa has a global ocean of liquid water under a thick ice crust. Many scientists think that Europa may offer the most favorable environment in the solar system to search for life.

### [12.3 Titan and Triton](#)

Saturn's moon Titan has an atmosphere that is thicker than that of Earth. There are lakes and rivers of liquid hydrocarbons, and evidence of a cycle of evaporation, condensation, and return to the surface that is similar to the water cycle on Earth (but with liquid methane and ethane). The Cassini-Huygens lander set down on Titan and showed a scene with boulders, made of water ice, frozen harder than rock. Neptune's cold moon Triton has a very thin atmosphere and nitrogen gas geysers.

### [12.4 Pluto and Charon](#)

Pluto and Charon have been revealed by the New Horizons spacecraft to be two of the most fascinating objects in the outer solar system. Pluto is small (a dwarf planet) but also surprisingly active, with contrasting areas of dark cratered terrain, light-colored basins of nitrogen ice, and mountains of frozen water that may be floating in the nitrogen ice. Even Pluto's largest moon Charon shows evidence of geological activity. Both Pluto and Charon turn out to be far more dynamic and interesting than could have been imagined before the New Horizons mission.

### [12.5 Planetary Rings \(and Enceladus\)](#)

Rings are composed of vast numbers of individual particles orbiting so close to a planet that its gravitational forces could have broken larger pieces apart or kept small pieces from gathering together. Saturn's rings are broad, flat, and nearly continuous, except for a handful of gaps. The particles are mostly water ice, with typical dimensions of a few centimeters. One Saturn moon, Enceladus, is today erupting geysers of water to maintain the tenuous E Ring, which is composed of very small ice crystals. The rings of Uranus are narrow ribbons separated by wide gaps and contain much less mass. Neptune's rings are similar but contain even less material. Much of the complex structure of the rings is due to waves and resonances induced by moons within the rings or orbiting outside them. The origin and age of each of these ring systems is still a mystery.



## For Further Exploration

**Articles****Moons**

Carroll, M. "Titan: What We've Learned about a Strange New World." *Astronomy* (March 2010): 30. Nice review of Cassini mission results.

Elliot, J. "The Warming Wisps of Triton." *Sky & Telescope* (February 1999): 42. About Neptune's intriguing moon.

Hayes, A., "Secrets from Titan's Seas." *Astronomy* (October 2015): 24. Good review of what we now know and what puzzles us about the hydrocarbon lakes of Titan.

Jewitt, D., et al. "The Strangest Satellites in the Solar System." *Scientific American* (August 2006): 40. Small irregular moons in the outer solar system.

Lakdawalla, E. "Ice Worlds of the Ringed Planet." *Sky & Telescope* (June 2009): 27. On the Cassini mission exploration of Enceladus, Iapetus, and other moons.

Mackenzie, D. "Is There Life under the Ice?" *Astronomy* (August 2001): 32. On future exploration of Europa.

Robertson, D. "Where Goes the Rain?" *Sky & Telescope* (March 2013): 26. About the methane weather cycle on Titan and what Cassini experiments are telling us.

Scharf, C. "A Universe of Dark Oceans." *Sky & Telescope* (December 2014): 20. Subsurface oceans on Europa, Ganymede, Enceladus, and Titan.

Showalter, M. "How to Catch a Moon (or Two) of Pluto." *Astronomy Beat* (December 2012): <http://www.astrosociety.org/wp-content/uploads/2013/02/ab2012-106.pdf>. On the discovery of small moons around Pluto, written by the person who discovered two of them.

Spencer, J. "Galileo's Closest Look at Io." *Sky & Telescope* (May 2001): 40.

Talcott, R. "Cassini Flies through Enceladus' Geysers." *Astronomy* (March 2009): 32.

Zimmerman, R. "Does Methane Flow on Titan?" *Astronomy* (February 2014): 22. Ideas about lakes, channels, and rain.

**Pluto**

Stern, A. "Pluto: Up Close and Personal." *Astronomy* (July 2015): 22. Good summary of the history of understanding Pluto and our current knowledge on the eve of the New Horizons encounter.

Stern, A. "The Pluto System Explored." *Astronomy* (November 2015): 24. Fine review of what the team learned from the first few data downloads from New Horizons.

Tombaugh, C. "How I Found Pluto" *Astronomy Beat* (May 2009): <http://astrosociety.org/wp-content/uploads/2013/02/ab2009-23.pdf>.

**Rings**

Beatty, J. "Saturn's Amazing Rings." *Sky & Telescope* (May 2013): 18. Good 7-page summary of what we know.

Burns, J., et al. "Bejeweled Worlds." *Scientific American* (February 2002): 64. On rings throughout the solar system.

Elliot, J., et al. "Discovering the Rings of Uranus." *Sky & Telescope* (June 1977): 412.

Esposito, L. "The Changing Shape of Planetary Rings." *Astronomy* (September 1987): 6.

Sobel, D. "Secrets of the Rings." *Discover* (April 1994): 86. Discusses the outer planet ring systems.

Tiscareno, M. "Ringworld Revelations." *Sky & Telescope* (February 2007): 32. Cassini results about the rings of Saturn.

### Websites

*Note: Many of the sites about planets and planetary missions listed for [Other Worlds: An Introduction to the Solar System](#) and [The Giant Planets](#) also include good information about the moons of the planets.*

Cassini Mission to Saturn: <http://saturn.jpl.nasa.gov/> (<http://saturn.jpl.nasa.gov/>) and <http://www.esa.int/SPECIALS/Cassini-Huygens/index.html> (<http://www.esa.int/SPECIALS/Cassini-Huygens/index.html>) and <http://ciclops.org> (<http://ciclops.org>)

Jupiter's Moons, at JPL: <http://solarsystem.nasa.gov/planets/jupiter/moons> (<http://solarsystem.nasa.gov/planets/jupiter/moons>)

Neptune's Moons, at JPL: <http://solarsystem.nasa.gov/planets/neptune/moons> (<http://solarsystem.nasa.gov/planets/neptune/moons>)

New Horizons Mission: <http://pluto.jhuapl.edu>. (<http://pluto.jhuapl.edu>) Provides information and images from the Pluto encounter, plus lots of background information.

Pluto, at JPL: <http://solarsystem.nasa.gov/planets/pluto> (<http://solarsystem.nasa.gov/planets/pluto>)

Saturn's Moons, at JPL: <http://solarsystem.nasa.gov/planets/saturn/moons> (<http://solarsystem.nasa.gov/planets/saturn/moons>)

Uranus' Moons, at JPL: <http://solarsystem.nasa.gov/planets/uranus/moons> (<http://solarsystem.nasa.gov/planets/uranus/moons>)

### Apps

Two apps you can buy for iPhones or iPads can show you the positions and features of the moons of Jupiter and Saturn for any selected date:

- Jupiter Atlas: <https://apps.apple.com/us/app/jupiter-atlas/id352033947> (<https://apps.apple.com/us/app/jupiter-atlas/id352033947>)
- Saturn Atlas: <https://apps.apple.com/us/app/saturn-atlas/id352038051> (<https://apps.apple.com/us/app/saturn-atlas/id352038051>)

### Videos

Amazing Moons: <https://www.youtube.com/watch?v=CQjZf2bW9XQ> (<https://www.youtube.com/watch?v=CQjZf2bW9XQ>). 2016 NASA video on intriguing moons in our solar system (4:16).

Briny Breath of Enceladus: <http://www.jpl.nasa.gov/video/details.php?id=846> (<http://www.jpl.nasa.gov/video/details.php?id=846>). Brief 2009 JPL film on the geysers of Enceladus (2:36).

Dr. Carolyn Porco's TED Talk on Enceladus: <https://www.youtube.com/watch?v=TRQdHrGuVgI> (<https://www.youtube.com/watch?v=TRQdHrGuVgI>) (3:26).

Titan: <http://www.youtube.com/watch?v=iTrOFefYxFg> (<http://www.youtube.com/watch?v=iTrOFefYxFg>). Video from Open University, with interviews, animations, and images (8:11).

Europa Mission: [http://www.jpl.nasa.gov/events/lectures\\_archive.php?year=2016&month=2](http://www.jpl.nasa.gov/events/lectures_archive.php?year=2016&month=2) ([http://www.jpl.nasa.gov/events/lectures\\_archive.php?year=2016&month=2](http://www.jpl.nasa.gov/events/lectures_archive.php?year=2016&month=2)). 2016 talk by two JPL scientists on NASA's plans for a mission to Jupiter's moon, which may have an underground liquid ocean (1:26:22).

Great Planet Debate: <http://gpd.jhuapl.edu/debate/debateStream.php> (<http://gpd.jhuapl.edu/debate/>)

[debateStream.php](#)). Neil deGrasse Tyson debates Mark Sykes about how to characterize Pluto, in 2008 (1:14:11).

How I Killed Pluto and Why It Had It Coming: [http://www.youtube.com/watch?v=7pbj\\_llmiMg](http://www.youtube.com/watch?v=7pbj_llmiMg) ([http://www.youtube.com/watch?v=7pbj\\_llmiMg](http://www.youtube.com/watch?v=7pbj_llmiMg)). 2011 Silicon Valley Astronomy Lecture by Michael Brown on the “demotion” of Pluto to a dwarf planet (1:27:13).

Seeking Pluto’s Frigid Heart: [https://www.youtube.com/watch?v=jxQXGTI\\_mo](https://www.youtube.com/watch?v=jxQXGTI_mo) ([https://www.youtube.com/watch?v=jxQXGTI\\_mo](https://www.youtube.com/watch?v=jxQXGTI_mo)). Dramatic 2016 *New York Times* production, narrated by Dennis Overbye (7:43).

Saturn’s Restless Rings: <https://www.youtube.com/watch?v=X5zcrEze8L4> (<https://www.youtube.com/watch?v=X5zcrEze8L4>). 2013 talk by Mark Showalter in the Silicon Valley Astronomy Lecture Series (1:30:59).

### Collaborative Group Activities

- A. Imagine it’s the distant future and humans can now travel easily among the planets. Your group is a travel agency, with the task of designing a really challenging tour of the Galilean moons for a group of sports enthusiasts. What kinds of activities are possible on each world? How would rock climbing on Ganymede, for example, differ from rock climbing on Earth? (If you design an activity for Io, you had better bring along very strong radiation shielding. Why?)
- B. In the same spirit as [Activity A](#), have your agency design a tour that includes the seven most spectacular sights of any kind on all the moons or rings covered in this chapter. What are the not-to-be-missed destinations that future tourists will want to visit and why? Which of the sights you pick are going to be spectacular if you are on the moon’s surface or inside the ring, and which would look interesting only from far away in space?
- C. In this chapter we could cover only a few of the dozens of moons in the outer solar system. Using the Internet or your college library, organize your group into a research team and find out more about one of the moons we did not cover in detail. Our favorites include Uranus’ Miranda, with its jigsaw puzzle surface; Saturn’s Mimas, with a “knockout” crater called Herschel; and Saturn’s Iapetus, whose two hemispheres differ significantly. Prepare a report to attract tourists to the world you selected.
- D. In a novel entitled *2010*, science fiction writer Arthur C. Clarke, inspired by the information coming back from the Voyager spacecraft, had fun proposing a life form under the ice of Europa that was evolving toward intelligence. Suppose future missions do indeed find some sort of life (not necessarily intelligent but definitely alive) under the ice of Europa—life that evolved completely independently from life on Earth. Have your group discuss what effect such a discovery would have on humanity’s view of itself. What should be our attitude toward such a life form? Do we have an obligation to guard it against contamination by our microbes and viruses? Or, to take an extreme position, should we wipe it out before it becomes competitive with Earth life or contaminates our explorers with microorganisms we are not prepared to deal with? Who should be in charge of making such decisions?
- E. In the same spirit as [Activity D](#), your group may want to watch the 2013 science fiction film *Europa Report*. The producers tried to include good science in depicting what it would be like for astronauts to visit that jovian moon. How well does your group think they did?
- F. A number of modern science fiction writers (especially those with training in science) have written short stories that take place on the moons of Jupiter and Saturn. There is a topical listing of science fiction stories with good astronomy at <http://bit.ly/astroscifi>. Members of your group can look under “Jupiter” or “Saturn” and find a story that interests you and then report on it to the whole class.
- G. Work together to make a list of all the reasons it is hard to send a mission to Pluto. What compromises had to be made so that the New Horizons mission was affordable? How would you design a second mission to learn more about the Pluto system?

- H. Your group has been asked by NASA to come up with one or more missions to learn about Europa. Review what we know about this moon so far and then design a robotic mission that would answer some of the questions we have. You can assume that budget is not a factor, but your instruments have to be realistic. (Bear in mind that Europa is cold and far from the Sun.)
- I. Imagine your group is the first landing party on Pluto (let's hope you remembered to bring long underwear!). You land in a place where Charon is visible in the sky and you observe Charon for one Earth week. Describe what Charon will look like during that week. Now you move your camp to the opposite hemisphere of Pluto. What will Charon look like there during the course of a week?
- J. When, in 2006, the International Astronomical Union (IAU) decided that Pluto should be called a dwarf planet and not a planet, they set up three criteria that a world must meet to be called a planet. Your group should use the Internet to find these criteria. Which of them did Pluto not meet? Read a little bit about the reaction to the IAU's decision among astronomers and the public. How do members of your group feel about Pluto's new classification? (After you have discussed it within the group, you may want to watch *The Great Planet Debate* video recommended in "For Further Exploration.")

## Exercises

### Review Questions

1. What are the moons of the outer planets made of, and how is their composition different from that of our Moon?
2. Compare the geology of Callisto, Ganymede, and Titan.
3. What is the evidence for a liquid water ocean on Europa, and why is this interesting to scientists searching for extraterrestrial life?
4. Explain the energy source that powers the volcanoes of Io.
5. Compare the properties of Titan's atmosphere with those of Earth's atmosphere.
6. How was Pluto discovered? Why did it take so long to find it?
7. How are Triton and Pluto similar?
8. Describe and compare the rings of Saturn and Uranus, including their possible origins.
9. Why were the rings of Uranus not observed directly from telescopes on the ground on Earth? How were they discovered?
10. List at least three major differences between Pluto and the terrestrial planets.
11. The Hubble Space Telescope images of Pluto in 2002 showed a bright spot and some darker areas around it. Now that we have the close-up New Horizons images, what did the large bright region on Pluto turn out to be?
12. Saturn's E ring is broad and thin, and far from Saturn. It requires fresh particles to sustain itself. What is the source of new E-ring particles?

### Thought Questions

13. Why do you think the outer planets have such extensive systems of rings and moons, while the inner planets do not?
14. Ganymede and Callisto were the first icy objects to be studied from a geological point of view. Summarize the main differences between their geology and that of the rocky terrestrial planets.

15. Compare the properties of the volcanoes on Io with those of terrestrial volcanoes. Give at least two similarities and two differences.
16. Would you expect to find more impact craters on Io or Callisto? Why?
17. Why is it unlikely that humans will be traveling to Io? (Hint: Review the information about Jupiter's magnetosphere in [The Giant Planets](#).)
18. Why do you suppose the rings of Saturn are made of bright particles, whereas the particles in the rings of Uranus and Neptune are black?
19. Suppose you miraculously removed all of Saturn's moons. What would happen to its rings?
20. We have a lot of good images of the large moons of Jupiter and Saturn from the Galileo and Cassini spacecraft missions (check out NASA's Planetary Photojournal site, at <http://photojournal.jpl.nasa.gov>, to see the variety). Now that the New Horizons mission has gone to Pluto, why don't we have as many good images of all sides of Pluto and Charon?
21. In the Star Wars movie *Star Wars Episode VI: Return of the Jedi*, a key battle takes place on the inhabited "forest moon" Endor, which supposedly orbits around a gas giant planet. From what you have learned about planets and moons of the solar system, why would this be an unusual situation?

### Figuring for Yourself

22. Which would have the longer orbital period: a moon 1 million km from the center of Jupiter, or a moon 1 million km from the center of Earth? Why?
23. How close to Uranus would a spacecraft have to get to obtain the same resolution as in [Example 12.1](#) with a camera that has an angular resolution of 2 arcsec?
24. Saturn's A, B, and C Rings extend 75,000 to 137,000 km from the center of the planet. Use Kepler's third law to calculate the difference between how long a particle at the inner edge and a particle at the outer edge of the three-ring system would take to revolve about the planet.
25. Use the information in [Appendix G](#) to calculate what you would weigh on Titan, Io, and Uranus' moon Miranda.
26. The average distance of Enceladus from Saturn is 238,000 km; the average distance of Titan from Saturn is 1,222,000 km. How much longer does it take Titan to orbit Saturn compared to Enceladus?