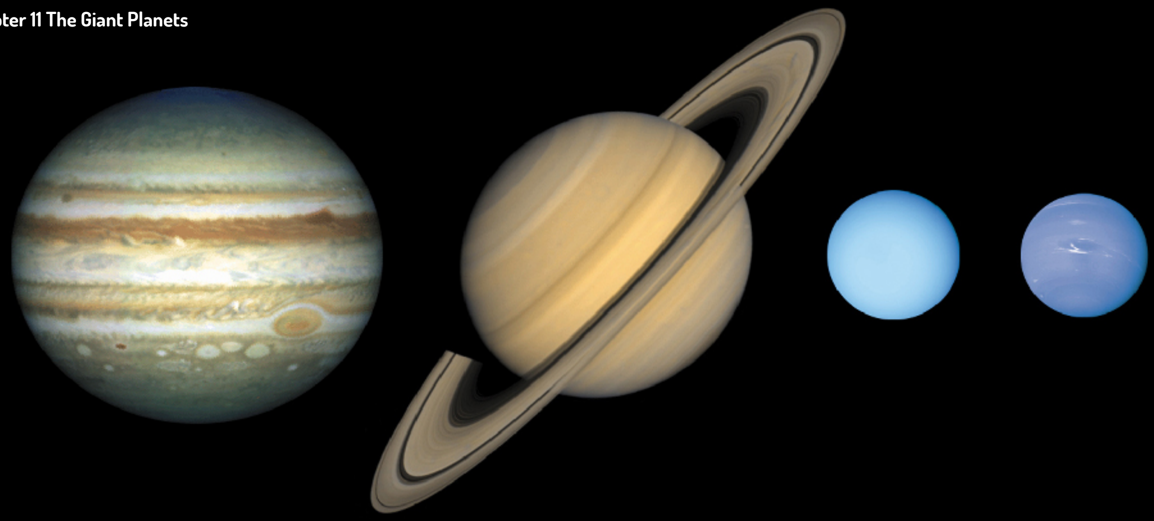
Astro-nomy



11

THE GIANT PLANETS

Figure 11.1 Giant Planets. The four giant planets in our solar system all have hydrogen atmospheres, but the warm gas giants, Jupiter and Saturn, have tan, beige, red, and white clouds that are thought to be composed of ammonia ice particles with various colorants called "chromophores." The blue-tinted ice giants, Uranus and Neptune, are much colder and covered in methane ice clouds. (credit: modification of work by Lunar and Planetary Institute, NASA)

Chapter Outline

Thinking Ahead

"What do we learn about the Earth by studying the planets? Humility."—Andrew Ingersoll discussing the results of the Voyager mission in 1986.

Beyond Mars and the asteroid belt, we encounter a new region of the solar system: the realm of the giants. Temperatures here are lower, permitting water and other volatiles to condense as ice. The planets are much larger, distances between them are much greater, and each giant world is accompanied by an extensive system of moons and rings.

From many perspectives, the outer solar system is where the action is, and the giant planets are the most important members of the Sun's family. When compared to these outer giants, the little cinders of rock and metal that orbit closer to the Sun can seem insignificant. These four giant worlds—Jupiter, Saturn, Uranus, Neptune—are the subjects of this chapter. Their rings, moons, and the dwarf planet Pluto are discussed in a later chapter.

11.1 EXPLORING THE OUTER PLANETS

Learning Objectives

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

- Provide an overview of the composition of the giant planets
- Chronicle the robotic exploration of the outer solar system
- Summarize the missions sent to orbit the gas giants

The giant planets hold most of the mass in our planetary system. Jupiter alone exceeds the mass of all the other planets combined (Figure 11.2). The material available to build these planets can be divided into three classes by what they are made of: "gases," "ices," and "rocks" (see Table 11.1). The "gases" are primarily hydrogen and helium, the most abundant elements in the universe. The way it is used here, the term "ices" refers to composition only and not whether a substance is actually in a solid state. "Ices" means compounds that form from the next most abundant elements: oxygen, carbon, and nitrogen. Common ices are water, methane, and ammonia, but ices may also include carbon monoxide, carbon dioxide, and others. "Rocks" are even less abundant than ices, and include everything else: magnesium, silicon, iron, and so on.

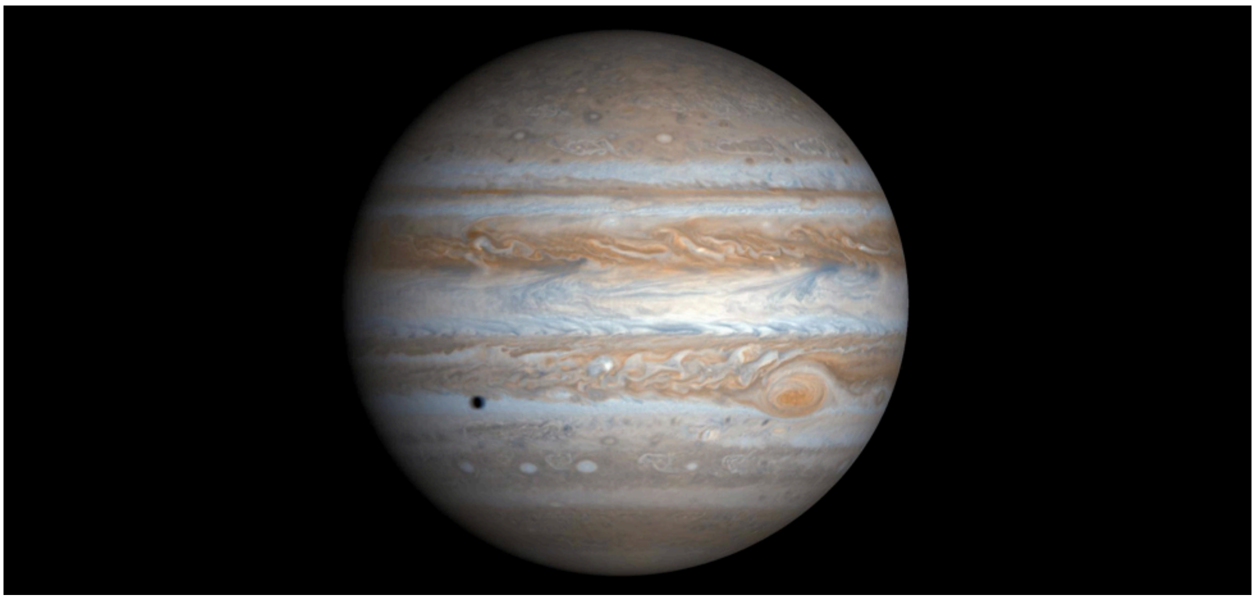


Figure 11.2 Jupiter. The Cassini spacecraft imaged Jupiter on its way to Saturn in 2012. The giant storm system called the Great Red Spot is visible to the lower right. The dark spot to the lower left is the shadow of Jupiter's moon Europa. (credit: modification of work by NASA/JPL)

Abundances in the Outer Solar System

Type of Material	Name	Approximate % (by Mass)
Gas	Hydrogen (H_2)	75
Gas	Helium (He)	24
Ice	Water (H_2O)	0.6
Ice	Methane (CH_4)	0.4
Ice	Ammonia (NH_3)	0.1
Rock	Magnesium (Mg), iron (Fe), silicon (Si)	0.3

Table 11.1

In the outer solar system, gases dominate the two largest planets, Jupiter and Saturn, hence their nickname "gas giants." Uranus and Neptune are called "ice giants" because their interiors contain far more of the "ice" component than their larger cousins. The chemistry for all four giant planet atmospheres is dominated by hydrogen. This hydrogen caused the chemistry of the outer solar system to become *reducing,* meaning that other elements tend to combine with hydrogen first. In the early solar system, most of the oxygen combined with hydrogen to make H_2O and was thus unavailable to form the kinds of oxidized compounds with other elements that are more familiar to us in the inner solar system (such as CO_2). As a result, the compounds detected in the atmosphere of the giant planets are mostly hydrogen-based gases such as methane (CH_4) and ammonia (NH_3), or more complex hydrocarbons (combinations of hydrogen and carbon) such as ethane (C_2H_6) and acetylene (C_2H_2).

Exploration of the Outer Solar System So Far

Eight spacecraft, seven from the United States and one from Europe, have penetrated beyond the asteroid belt into the realm of the giants. Table 11.2 summarizes the spacecraft missions to the outer solar system.

Missions to the Giant Planets

Planet	Spacecraft[1]	Encounter Date	Type
Jupiter	Pioneer 10	December 1973	Flyby
	Pioneer 11	December 1974	Flyby
	Voyager 1	March 1979	Flyby
	Voyager 2	July 1979	Flyby
	Ulysses	February 1992	Flyby during gravity assist
	Galileo	December 1995	Orbiter and probe
	Cassini	December 2002	Flyby
	New Horizons	February 2007	Flyby during gravity assist
	Juno	July 2016	Orbiter
Saturn	Pioneer 11	September 1979	Flyby
	Voyager 1	November 1980	Flyby
	Voyager 2	August 1981	Flyby
	Cassini	July 2004 (Saturn orbit injection 2000)	Orbiter

Table 11.2

1 Both the Ulysses and the New Horizons spacecraft (designed to study the Sun and Pluto, respectively) flew past Jupiter for a gravity boost (gaining energy by "stealing" a little bit from the giant planet's rotation).

Missions to the Giant Planets

Planet	Spacecraft	Encounter Date	Type
Uranus	Voyager 2	January 1986	Flyby
Neptune	Voyager 2	August 1989	Flyby

Table 11.2

The challenges of exploring so far away from Earth are considerable. Flight times to the giant planets are measured in years to decades, rather than the months required to reach Venus or Mars. Even at the speed of light, messages take hours to pass between Earth and the spacecraft. If a problem develops near Saturn, for example, a wait of hours for the alarm to reach Earth and for instructions to be routed back to the spacecraft could spell disaster. Spacecraft to the outer solar system must therefore be highly reliable and capable of a greater degree of independence and autonomy. Outer solar system missions also must carry their own power sources since the Sun is too far away to provide enough energy. Heaters are required to keep instruments at proper operating temperatures, and spacecraft must have radio transmitters powerful enough to send their data to receivers on distant Earth.

The first spacecraft to investigate the regions past Mars were the NASA Pioneers 10 and 11, launched in 1972 and 1973 as pathfinders to Jupiter. One of their main objectives was simply to determine whether a spacecraft could actually navigate through the belt of asteroids that lies beyond Mars without getting destroyed by collisions with asteroidal dust. Another objective was to measure the radiation hazards in the *magnetosphere* (or zone of magnetic influence) of Jupiter. Both spacecraft passed through the asteroid belt without incident, but the energetic particles in Jupiter's magnetic field nearly wiped out their electronics, providing information necessary for the safe design of subsequent missions.

Pioneer 10 flew past Jupiter in 1973, after which it sped outward toward the limits of the solar system. Pioneer 11 undertook a more ambitious program, using the gravity of Jupiter to aim for Saturn, which it reached in 1979. The twin Voyager spacecraft launched the next wave of outer planet exploration in 1977. Voyagers 1 and 2 each carried 11 scientific instruments, including cameras and spectrometers, as well as devices to measure the characteristics of planetary magnetospheres. Since they kept going outward after their planetary encounters, these are now the most distant spacecraft ever launched by humanity.

Voyager 1 reached Jupiter in 1979 and used a gravity assist from that planet to take it on to Saturn in 1980. Voyager 2 arrived at Jupiter four months later, but then followed a different path to visit all the outer planets, reaching Saturn in 1981, Uranus in 1986, and Neptune in 1989. This trajectory was made possible by the approximate alignment of the four giant planets on the same side of the Sun. About once every 175 years, these planets are in such a position, and it allows a single spacecraft to visit them all by using gravity-assisted flybys to adjust course for each subsequent encounter; such a maneuver has been nicknamed a "Grand Tour" by astronomers.

LINK TO LEARNING

The Jet Propulsion Laboratory has a nice video called **Voyager: The Grand Tour (https://openstax.org/**

l/30JPLGrandT) that describes the Voyager mission and what it found.

MAKING CONNECTIONS

Engineering and Space Science: Teaching an Old Spacecraft New Tricks

By the time Voyager 2 arrived at Neptune in 1989, 12 years after its launch, the spacecraft was beginning to show signs of old age. The arm on which the camera and other instruments were located was “arthritic”: it could no longer move easily in all directions. The communications system was “hard of hearing”: part of its radio receiver had stopped working. The “brains” had significant “memory loss”: some of the onboard computer memory had failed. And the whole spacecraft was beginning to run out of energy: its generators had begun showing serious signs of wear.

To make things even more of a challenge, Voyager’s mission at Neptune was in many ways the most difficult of all four flybys. For example, since sunlight at Neptune is 900 times weaker than at Earth, the onboard camera had to take much longer exposures in this light-starved environment. This was a nontrivial requirement, given that the spacecraft was hurtling by Neptune at ten times the speed of a rifle bullet.

The solution was to swivel the camera backward at exactly the rate that would compensate for the forward motion of the spacecraft. Engineers had to preprogram the ship’s computer to execute an incredibly complex series of maneuvers for each image. The beautiful Voyager images of Neptune are a testament to the ingenuity of spacecraft engineers.

The sheer distance of the craft from its controllers on Earth was yet another challenge. Voyager 2 received instructions and sent back its data via on-board radio transmitter. The distance from Earth to Neptune is about 4.8 billion kilometers. Over this vast distance, the power that reached us from Voyager 2 at Neptune was approximately10^{-16} watts, or 20 billion times less power than it takes to operate a digital watch. Thirty-eight different antennas on four continents were used by NASA to collect the faint signals from the spacecraft and decode the precious information about Neptune that they contained.

Enter the Orbiters: Galileo, Cassini, and Juno

The Pioneer and Voyager missions were flybys of the giant planets: they each produced only quick looks before the spacecraft sped onward. For more detailed studies of these worlds, we require spacecraft that can go into orbit around a planet. For Jupiter and Saturn, these orbiters were the Galileo, Cassini, and Juno spacecraft. To date, no orbiter missions have been started for Uranus and Neptune, although planetary scientists have expressed keen interest.

The Galileo spacecraft was launched toward Jupiter in 1989 and arrived in 1995. Galileo began its investigations by deploying an entry probe into Jupiter, for the first direct studies of the planet’s outer atmospheric layers.

The probe plunged at a shallow angle into Jupiter’s atmosphere, traveling at a speed of 50 kilometers *per second*—that’s fast enough to fly from New York to San Francisco in 100 seconds! This was the highest speed at which any probe has so far entered the atmosphere of a planet, and it put great demands on the heat shield protecting it. The high entry speed was a result of acceleration by the strong gravitational attraction of Jupiter.

Atmospheric friction slowed the probe within 2 minutes, producing temperatures at the front of its heat shield as high as 15,000 °C. As the probe's speed dropped to 2500 kilometers per hour, the remains of the glowing heat shield were jettisoned, and a parachute was deployed to lower the instrumented probe spacecraft more gently into the atmosphere (**Figure 11.3**). The data from the probe instruments were relayed to Earth via the main Galileo spacecraft.

(a) (b)

Figure 11.3 Galileo Probe Falling into Jupiter. Galileo Probe and Juno Image of Jupiter's South Pole. (a) This artist's depiction shows the Galileo probe descending into the clouds via parachute just after the protective heat shield separated. The probe made its measurements of Jupiter's atmosphere on December 7, 1995. (b) This Juno image, taken in 2017 from about 100,000 kilometers above the cloudtops, shows the south polar region of Jupiter with its dramatic complex of storms and clouds. The enhanced-color image was processed for NASA/JPL by citizen scientist John Landino. (credit a: modification of work by NASA/Ames Research Center; credit b: modification of work by NASA/JPL-Caltech/SwRI/MSSS/John Landino)

The probe continued to operate for an hour, descending 200 kilometers into the atmosphere. A few minutes later the polyester parachute melted, and within a few hours the main aluminum and titanium structure of the probe vaporized to become a part of Jupiter itself. About 2 hours after receipt of the final probe data, the main spacecraft fired its retro-rockets so it could be captured into orbit around the planet, where its primary objectives were to study Jupiter's large and often puzzling moons.

The Cassini mission to Saturn (**Figure 11.4**), a cooperative venture between NASA and the European Space Agency, was similar to Galileo in its two-fold approach. Launched in 1997, Cassini arrived in 2004 and went into orbit around Saturn, beginning extensive studies of its rings and moons, as well as the planet itself. In January 2005, Cassini deployed an entry probe into the atmosphere of Saturn's large moon, Titan, where it successfully landed on the surface. (We'll discuss the probe and what it found in the chapter on **Rings, Moons, and Pluto**.)

The Voyager and Galileo missions to Jupiter were primarily designed to study the moons and the atmosphere of the planet. The next NASA mission, an orbiter called Juno, arrived at Jupiter in July 2016. In order to meet its objectives of studying the jovian magnetosphere, it has a very elongated (eccentric) 55-day orbit, that takes it from 4 thousand kilometers above the cloud tops out to 76 thousand kilometers. The orbit takes the craft over Jupiter's poles, giving us remarkable close-ups of the polar regions (previous spacecraft viewed the planet from lower latitudes).

Juno was originally designed without a camera, but fortunately scientists rectified this omission, adding a simple downward-looking color camera to use during close passes by Jupiter. Recognizing the value of such images, both scientific and artistic, it was decided to post the raw images and encourage "citizen scientists" to process them. The product has been many dramatic, brightly colored views of Jupiter, such as **Figure 11.3**.

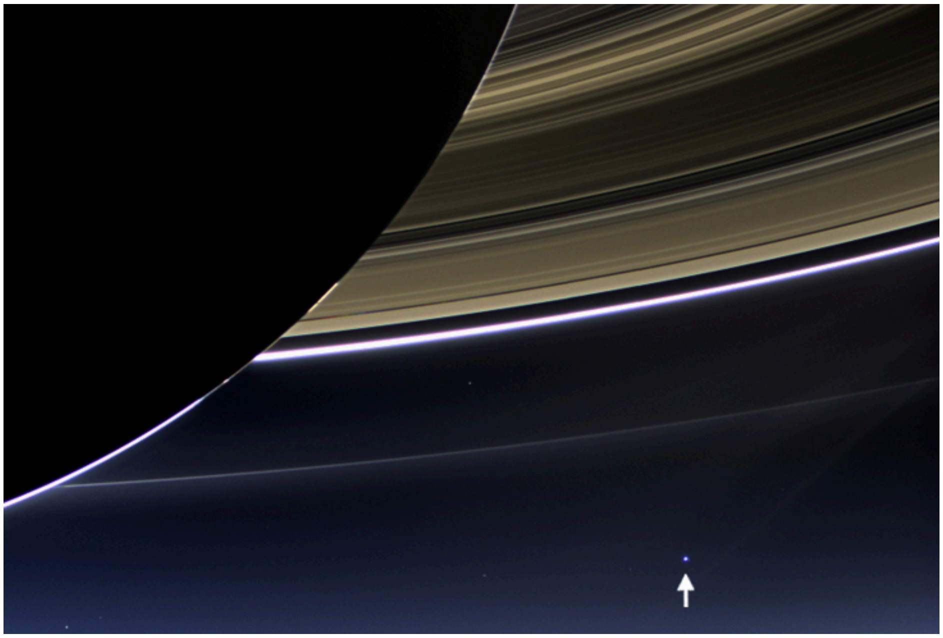


Figure 11.4 Earth as Seen from Saturn. This popular Cassini image shows Earth as a tiny dot (marked with an arrow) seen below Saturn's rings. It was taken in July 2013, when Saturn was 1.4 billion kilometers from Earth. (credit: modification of work by NASA/JPL-Caltech/Space Science Institute)

11.2 THE GIANT PLANETS

Learning Objectives

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

- Describe the basic physical characteristics, general appearance, and rotation of the giant planets
- Describe the composition and structure of Jupiter, Saturn, Uranus, and Neptune
- Compare and contrast the internal heat sources of the giant planets
- Describe the discovery and characteristics of the giant planets' magnetic fields

Let us now examine the four giant (or *jovian*) planets in more detail. Our approach is not just to catalog their characteristics, but to compare them with each other, noting their similarities and differences and attempting to relate their properties to their differing masses and distances from the Sun.

Basic Characteristics

The giant planets are very far from the Sun. Jupiter is more than five times farther from the Sun than Earth's distance (5 AU), and takes just under 12 years to circle the Sun. Saturn is about twice as far away as Jupiter (almost 10 AU) and takes nearly 30 years to complete one orbit. Uranus orbits at 19 AU with a period of 84 years, while Neptune, at 30 AU, requires 165 years for each circuit of the Sun. These long timescales make it difficult for us short-lived humans to study seasonal change on the outer planets.

Jupiter and Saturn have many similarities in composition and internal structure, although Jupiter is nearly four times more massive. Uranus and Neptune are smaller and differ in composition and internal structure from their large siblings. Some of the main properties of these four planets are summarized in Table 11.3.

Basic Properties of the Jovian Planets

Planet	Distance (AU)	Period (years)	Diameter (km)	Mass (Earth = 1)	Density (g/cm^3)	Rotation (hours)
Jupiter	5.2	11.9	142,800	318	1.3	9.9
Saturn	9.5	29.5	120,540	95	0.7	10.7
Uranus	19.2	84.1	51,200	14	1.3	17.2
Neptune	30.0	164.8	49,500	17	1.6	16.1

Table 11.3

Jupiter, the giant among giants, has enough mass to make 318 Earths. Its diameter is about 11 times that of Earth (and about one tenth that of the Sun). Jupiter's average density is 1.3 g/cm^3, much lower than that of any of the terrestrial planets. (Recall that water has a density of 1 g/cm^3.) Jupiter's material is spread out over a volume so large that more than 1400 Earths could fit within it.

Saturn's mass is 95 times that of Earth, and its average density is only 0.7 g/cm^3—the lowest of any planet. Since this is less than the density of water, Saturn would be light enough to float.

Uranus and Neptune each have a mass about 15 times that of Earth and, hence, are only 5% as massive as Jupiter. Their densities of 1.3 g/cm^3 and 1.6 g/cm^3, respectively, are much higher than that of Saturn. This is one piece of evidence that tells us that their composition must differ fundamentally from the gas giants. When astronomers began to discover other planetary systems (exoplanets), we found that planets the size of Uranus and Neptune are common, and that there are even more exoplanets intermediate in size between Earth and these ice giants, a type of planet not found in our solar system.

Appearance and Rotation

When we look at the planets, we see only their atmospheres, composed primarily of hydrogen and helium gas (see **Figure 11.1**). The uppermost clouds of Jupiter and Saturn, the part we see when looking down at these planets from above, are composed of ammonia crystals. On Neptune, the upper clouds are made of methane. On Uranus, we see no obvious cloud layer at all, but only a deep and featureless haze.

Seen through a telescope, Jupiter is a colorful and dynamic planet. Distinct details in its cloud patterns allow us to determine the rotation rate of its atmosphere at the cloud level, although such atmosphere rotation may have little to do with the spin of the underlying planet. Much more fundamental is the rotation of the mantle and core; these can be determined by periodic variations in radio waves coming from Jupiter, which are controlled by its magnetic field. Since the magnetic field (which we will discuss below) originates deep inside the planet, it shares the rotation of the interior. The rotation period we measure in this way is 9 hours 56 minutes, which gives Jupiter the shortest "day" of any planet. In the same way, we can measure that the underlying rotation period of Saturn is 10 hours 40 minutes. Uranus and Neptune have slightly longer rotation periods of about 17 hours, also determined from the rotation of their magnetic fields.

LINK TO LEARNING

A brief video made from Hubble Space Telescope photos shows **the rotation of Jupiter (https://openstax.org/l/30HSTJupRot)** with its many atmospheric features.

Remember that Earth and Mars have seasons because their spin axes, instead of “standing up straight,” are tilted relative to the orbital plane of the solar system. This means that as Earth revolves around the Sun, sometimes one hemisphere and sometimes the other “leans into” the Sun.

What are the seasons like for the giant planets? The spin axis of Jupiter is tilted by only 3°, so there are no seasons to speak of. Saturn, however, does have seasons, since its spin axis is inclined at 27° to the perpendicular to its orbit. Neptune has about the same tilt as Saturn (29°); therefore, it experiences similar seasons (only more slowly). The strangest seasons of all are on Uranus, which has a spin axis tilted by 98° with respect to the north direction. Practically speaking, we can say that Uranus orbits on its side, and its ring and moon system follow along, orbiting about Uranus’ equator (**Figure 11.5**).

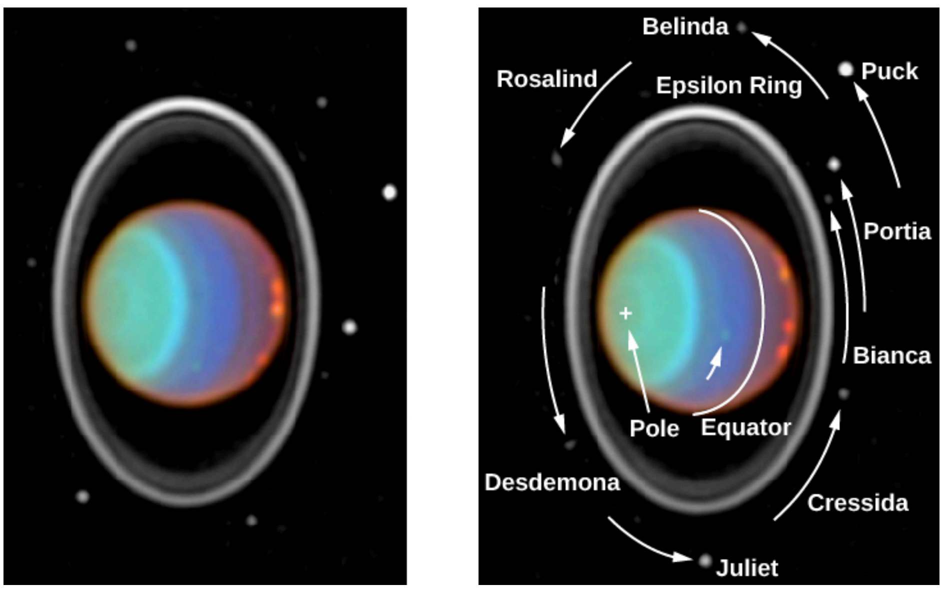


Figure 11.5 Infrared Image of Uranus. The infrared camera on the Hubble Space Telescope took these false-color images of the planet Uranus, its ring system, and moons in 1997. The south pole of the planet (marked with a “+” on the right image) faces the Sun; its green color shows a strong local haze. The two images were taken 90 minutes apart, and during that time the five reddish clouds can be seen to rotate around the parallel to the equator. The rings (which are very faint in the visible light, but prominent in infrared) and eight moons can be seen around the equator. This was the “bull’s eye” arrangement that Voyager saw as it approached Uranus in 1986. (credit: modification of work by Erich Karkoschka (University of Arizona), and NASA/ESA)

We don’t know what caused Uranus to be tipped over like this, but one possibility is a collision with a large planetary body when our system was first forming. Whatever the cause, this unusual tilt creates dramatic seasons. When Voyager 2 arrived at Uranus, its south pole was facing directly into the Sun. The southern hemisphere was experiencing a 21-year sunlit summer, while during that same period the northern hemisphere was plunged into darkness. For the next 21-year season, the Sun shines on Uranus’ equator, and both hemispheres go through cycles of light and dark as the planet rotates (**Figure 11.6**). Then there are 21 years of an illuminated northern hemisphere and a dark southern hemisphere. After that the pattern of alternating day and night repeats.

Just as on Earth, the seasons are even more extreme at the poles. If you were to install a floating platform at the south pole of Uranus, for example, it would experience 42 years of light and 42 years of darkness. Any future astronauts crazy enough to set up camp there could spend most of their lives without ever seeing the Sun.

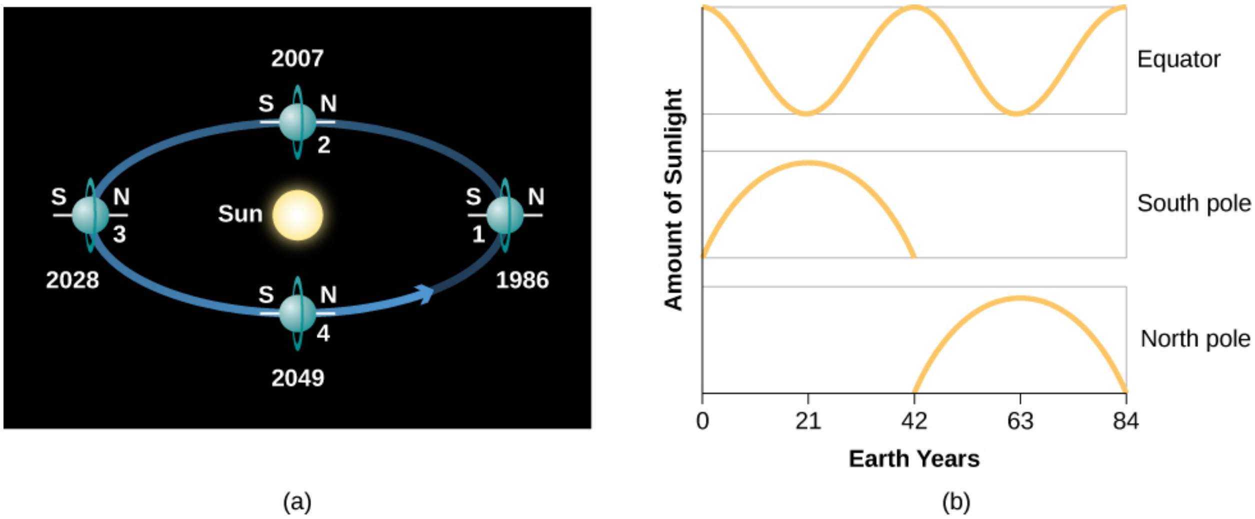


Figure 11.6 Strange Seasons on Uranus. (a) This diagram shows the orbit of Uranus as seen from above. At the time Voyager 2 arrived (position 1), the South Pole was facing the Sun. As we move counterclockwise in the diagram, we see the planet 21 years later at each step. (b) This graph compares the amount of sunlight seen at the poles and the equator of Uranus over the course of its 84-year revolution around the Sun.

Composition and Structure

Although we cannot see into these planets, astronomers are confident that the interiors of Jupiter and Saturn are composed primarily of hydrogen and helium. Of course, these gases have been measured only in their atmosphere, but calculations first carried out more than 50 years ago showed that these two light gases are the only possible materials out of which a planet with the observed masses and densities of Jupiter and Saturn could be constructed.

The deep internal structures of these two planets are difficult to predict. This is mainly because these planets are so big that the hydrogen and helium in their centers become tremendously compressed and behave in ways that these gases can never behave on Earth. The best theoretical models we have of Jupiter's structure predict a central pressure greater than 100 million bars and a central density of about 31 g/cm^3. (By contrast, Earth's core has a central pressure of 4 million bars and a central density of 17 g/cm^3.)

At the pressures inside the giant planets, familiar materials can take on strange forms. A few thousand kilometers below the visible clouds of Jupiter and Saturn, pressures become so great that hydrogen changes from a gaseous to a liquid state. Still deeper, this liquid hydrogen is further compressed and begins to act like a metal, something it never does on Earth. (In a metal, electrons are not firmly attached to their parent nuclei but can wander around. This is why metals are such good conductors of electricity.) On Jupiter, the greater part of the interior is liquid metallic hydrogen.

Because Saturn is less massive, it has only a small volume of metallic hydrogen, but most of its interior is liquid. Uranus and Neptune are too small to reach internal pressures sufficient to liquefy hydrogen. We will return to the discussion of the metallic hydrogen layers when we examine the magnetic fields of the giant planets.

Each of these planets has a core composed of heavier materials, as demonstrated by detailed analyses of their gravitational fields. Presumably these cores are the original rock-and-ice bodies that formed before the capture of gas from the surrounding nebula. The cores exist at pressures of tens of millions of bars. While scientists speak of the giant planet cores being composed of rock and ice, we can be sure that neither rock nor ice assumes any familiar forms at such pressures and temperatures. Remember that what is really meant by "rock" is any material made up primarily of iron, silicon, and oxygen, while the term “ice” in this chapter denotes materials composed primarily of the elements carbon, nitrogen, and oxygen in combination with hydrogen.

Figure 11.7 illustrates the likely interior structures of the four jovian planets. It appears that all four have similar cores of rock and ice. On Jupiter and Saturn, the cores constitute only a few percent of the total mass, consistent with the initial composition of raw materials shown in **Table 11.1**. However, most of the mass of Uranus and Neptune resides in these cores, demonstrating that the two outer planets were unable to attract massive quantities of hydrogen and helium when they were first forming.

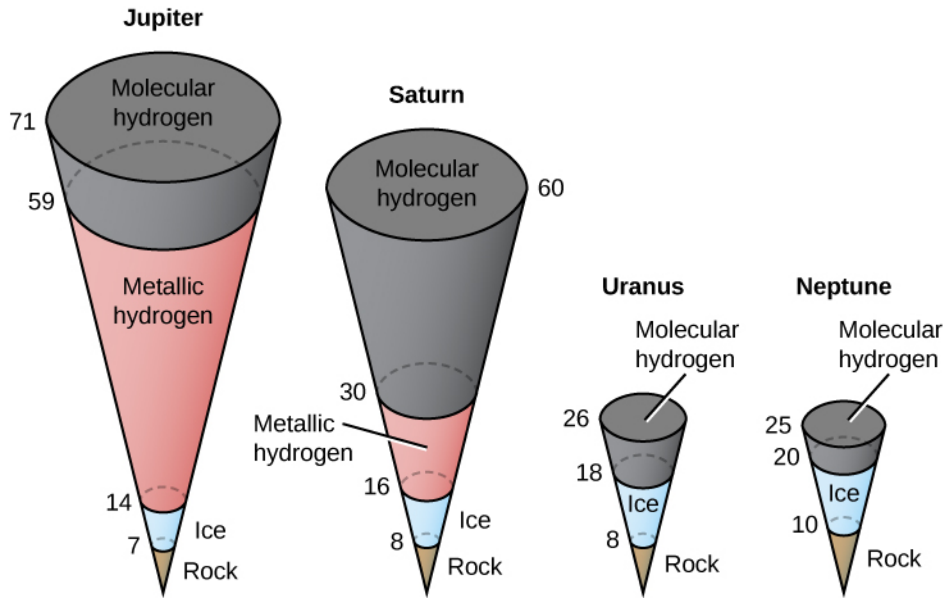


Figure 11.7 Internal Structures of the Jovian Planets. Jupiter and Saturn are composed primarily of hydrogen and helium (but hydrogen dominates), but Uranus and Neptune consist in large part of compounds of carbon, nitrogen, and oxygen. (The diagrams are drawn to scale; numbers show radii in thousands of kilometers.)

Internal Heat Sources

Because of their large sizes, all the giant planets were strongly heated during their formation by the collapse of surrounding material onto their cores. Jupiter, being the largest, was the hottest. Some of this primordial heat can still remain inside such large planets. In addition, it is possible for giant, largely gaseous planets to generate heat after formation by slowly contracting. (With so large a mass, even a minuscule amount of shrinking can generate significant heat.) The effect of these internal energy sources is to raise the temperatures in the interiors and atmospheres of the planets higher than we would expect from the heating effect of the Sun alone.

Jupiter has the largest internal energy source, amounting to 4×10^{17} watts; that is, it is heated from inside with energy equivalent to 4 million billion 100-watt lightbulbs. This energy is about the same as the total solar energy absorbed by Jupiter. The atmosphere of Jupiter is therefore something of a cross between a normal planetary atmosphere (like Earth’s), which obtains most of its energy from the Sun, and the atmosphere of a star, which is entirely heated by an internal energy source. Most of the internal energy of Jupiter is primordial heat, left over from the formation of the planet 4.5 billon years ago.

Saturn has an internal energy source about half as large as that of Jupiter, which means (since its mass is only about one quarter as great) that it is producing twice as much energy per kilogram of material as does Jupiter. Since Saturn is expected to have much less primordial heat, there must be another source at work generating most of this 2×10^{17} watts of power. This source is the separation of helium from hydrogen in Saturn’s interior. In the liquid hydrogen mantle, the heavier helium forms droplets that sink toward the core, releasing gravitational energy. In effect, Saturn is still differentiating—letting lighter material rise and heavier material fall.

Uranus and Neptune are different. Neptune has a small internal energy source, while Uranus does not emit a measurable amount of internal heat. As a result, these two planets have almost the same atmospheric temperature, in spite of Neptune's greater distance from the Sun. No one knows why these two planets differ in their internal heat, but all this shows how nature can contrive to make each world a little bit different from its neighbors.

Magnetic Fields

Each of the giant planets has a strong magnetic field, generated by electric currents in its rapidly spinning interior. Associated with the magnetic fields are the planets' *magnetospheres*, which are regions around the planet within which the planet's own magnetic field dominates over the general interplanetary magnetic field. The magnetospheres of these planets are their largest features, extending millions of kilometers into space.

In the late 1950s, astronomers discovered that Jupiter was a source of radio waves that got more intense at longer rather than at shorter wavelengths—just the reverse of what is expected from thermal radiation (radiation caused by the normal vibrations of particles within all matter). Such behavior is typical, however, of the radiation emitted when high-speed electrons are accelerated by a magnetic field. We call this **synchrotron radiation** because it was first observed on Earth in particle accelerators, called synchrotrons. This was our first hint that Jupiter must have a strong magnetic field.

Later observations showed that the radio waves are coming from a region surrounding Jupiter with a diameter several times that of the planet itself (Figure 11.8). The evidence suggested that a vast number of charged atomic particles must be circulating around Jupiter, spiraling around the lines of force of a magnetic field associated with the planet. This is just what we observe happening, but on a smaller scale, in the Van Allen belt around Earth. The magnetic fields of Saturn, Uranus, and Neptune, discovered by the spacecraft that first passed close to these planets, work in a similar way, but are not as strong.

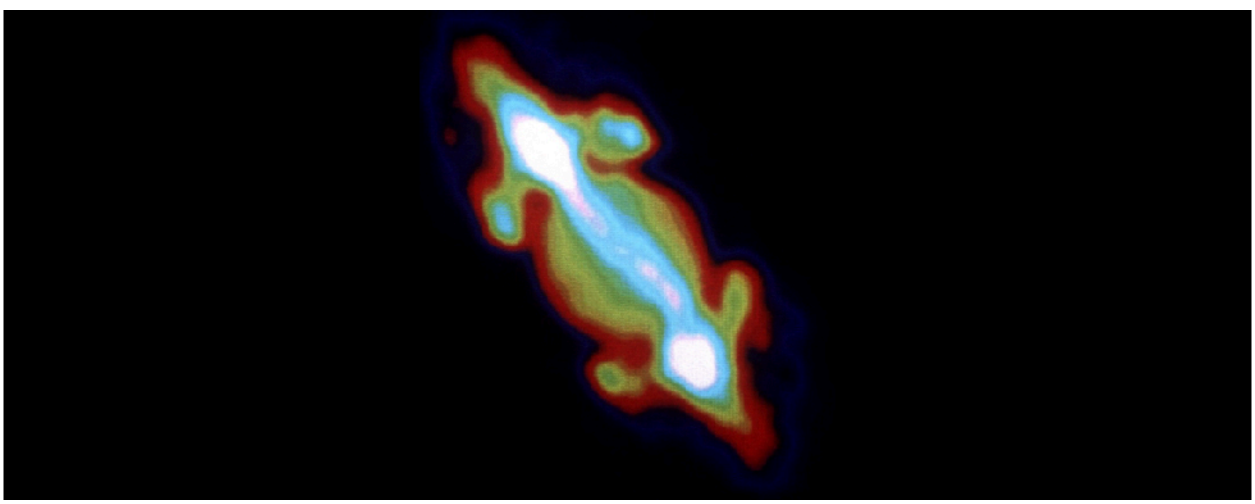


Figure 11.8 Jupiter in Radio Waves. This false-color image of Jupiter was made with the Very Large Array (of radio telescopes) in New Mexico. We see part of the magnetosphere, brightest in the middle because the largest number of charged particles are in the equatorial zone of Jupiter. The planet itself is slightly smaller than the green oval in the center. Different colors are used to indicate different intensities of synchrotron radiation. (credit: modification of work by I. de Pater (UC Berkeley) NRAO, AUI, NSF)

LINK TO LEARNING

Learn more about **the magnetosphere of Jupiter (https://openstax.org/l/30NASAJupMag)** and why we continue to be interested in it from this brief NASA video.

Inside each magnetosphere, charged particles spiral around in the magnetic field; as a result, they can be accelerated to high energies. These charged particles can come from the Sun or from the neighborhood of the planet itself. In Jupiter's case, Io, one of its moons, turns out to have volcanic eruptions that blast charged particles into space and right into the jovian magnetosphere.

The axis of Jupiter's magnetic field (the line that connects the magnetic north pole with the magnetic south pole) is not aligned exactly with the axis of rotation of the planet; rather, it is tipped by about 10°. Uranus and Neptune have even greater magnetic tilts, of 60° and 55°, respectively. Saturn's field, on the other hand, is perfectly aligned with its rotation axis. Why different planets have such different magnetic tilts is not well understood.

The physical processes around the jovian planets turn out to be milder versions of what astronomers find in many distant objects, from the remnants of dead stars to the puzzling distant powerhouses we call quasars. One reason to study the magnetospheres of the giant planets and Earth is that they provide nearby accessible analogues of more energetic and challenging cosmic processes.

11.3 ATMOSPHERES OF THE GIANT PLANETS

Learning Objectives

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

- Discuss the atmospheric composition of the giant planets
- Describe the cloud formation and atmospheric structure of the gas giants
- Characterize the giant planets' wind and weather patterns
- Understand the scale and longevity of storms on the giant planets

The atmospheres of the jovian planets are the parts we can observe or measure directly. Since these planets have no solid surfaces, their atmospheres are more representative of their general compositions than is the case with the terrestrial planets. These atmospheres also present us with some of the most dramatic examples of weather patterns in the solar system. As we will see, storms on these planets can grow bigger than the entire planet Earth.

Atmospheric Composition

When sunlight reflects from the atmospheres of the giant planets, the atmospheric gases leave their "fingerprints" in the spectrum of light. Spectroscopic observations of the jovian planets began in the nineteenth century, but for a long time, astronomers were not able to interpret the spectra they observed. As late as the 1930s, the most prominent features photographed in these spectra remained unidentified. Then better spectra revealed the presence of molecules of methane (CH_4) and ammonia (NH_3) in the atmospheres of Jupiter and Saturn.

At first astronomers thought that methane and ammonia might be the main constituents of these atmospheres, but now we know that hydrogen and helium are actually the dominant gases. The confusion arose because neither hydrogen nor helium possesses easily detected spectral features in the visible spectrum. It was not until the Voyager spacecraft measured the far-infrared spectra of Jupiter and Saturn that a reliable abundance for the elusive helium could be found.

The compositions of the two atmospheres are generally similar, except that on Saturn there is less helium as the result of the precipitation of helium that contributes to Saturn's internal energy source. The most precise measurements of composition were made on Jupiter by the Galileo entry probe in 1995; as a result, we know the abundances of some elements in the jovian atmosphere even better than we know those in the Sun.

VOYAGERS IN ASTRONOMY

James Van Allen: Several Planets under His Belt

The career of physicist James Van Allen spanned the birth and growth of the space age, and he played a major role in its development. Born in Iowa in 1914, Van Allen received his PhD from the University of Iowa. He then worked for several research institutions and served in the Navy during World War II.

After the war, Van Allen (**Figure 11.9**) was appointed Professor of Physics at the University of Iowa. He and his collaborators began using rockets to explore cosmic radiation in Earth's outer atmosphere. To reach extremely high altitudes, Van Allen designed a technique in which a balloon lifts and then launches a small rocket (the rocket is nicknamed "the rockoon").

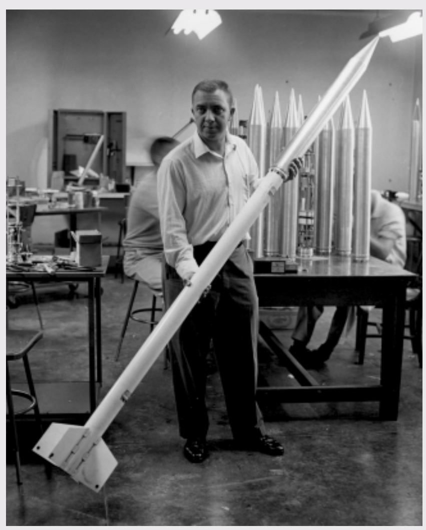


Figure 11.9 James Van Allen (1914–2006). In this 1950s photograph, Van Allen holds a "rockoon." (credit: modification of work by Frederick W. Kent Collection, University of Iowa Archives)

Over dinner one night in 1950, Van Allen and several colleagues came up with the idea of the International Geophysical Year (IGY), an opportunity for scientists around the world to coordinate their investigations of the physics of Earth, especially research done at high altitudes. In 1955, the United States and the Soviet Union each committed themselves to launching an Earth-orbiting satellite during IGY, a competition that began what came to be known as the space race. The IGY (stretched to 18 months) took place between July 1957 and December 1958.

The Soviet Union won the first lap of the race by launching Sputnik 1 in October 1957. The US government spurred its scientists and engineers to even greater efforts to get something into space to maintain the country’s prestige. However, the primary US satellite program, Vanguard, ran into difficulties: each of its early launches crashed or exploded. Simultaneously, a second team of rocket engineers and scientists had quietly been working on a military launch vehicle called Jupiter-C. Van Allen spearheaded the design of the instruments aboard a small satellite that this vehicle would carry. On January 31, 1958, Van Allen’s Explorer 1 became the first US satellite in space.

Unlike Sputnik, Explorer 1 was equipped to make scientific measurements of high-energy charged particles above the atmosphere. Van Allen and his team discovered a belt of highly charged particles surrounding Earth, and these belts now bear his name. This first scientific discovery of the space program made Van Allen’s name known around the world.

Van Allen and his colleagues continued to measure the magnetic and particle environment around planets with increasingly sophisticated spacecraft, including Pioneers 10 and 11, which made exploratory surveys of the environments of Jupiter and Saturn. Some scientists refer to the charged-particle zones around those planets as Van Allen belts as well. (Once, when Van Allen was giving a lecture at the University of Arizona, the graduate students in planetary science asked him if he would leave his belt at the school. It is now proudly displayed as the university’s “Van Allen belt.”)

Van Allen was a strong supporter of space science and an eloquent senior spokesperson for the American scientific community, warning NASA not to put all its efforts into human spaceflight, but to also use robotic spacecraft as productive tools for space exploration.

Clouds and Atmospheric Structure

The clouds of Jupiter (**Figure 11.10**) are among the most spectacular sights in the solar system, much beloved by makers of science-fiction films. They range in color from white to orange to red to brown, swirling and twisting in a constantly changing kaleidoscope of patterns. Saturn shows similar but much more subdued cloud activity; instead of vivid colors, its clouds have a nearly uniform butterscotch hue (**Figure 11.11**).

Figure 11.10 Jupiter's Colorful Clouds. The vibrant colors of the clouds on Jupiter present a puzzle to astronomers: given the cool temperatures and the composition of nearly 90% hydrogen, the atmosphere should be colorless. One hypothesis suggests that perhaps colorful hydrogen compounds rise from warm areas. The actual colors are a bit more muted, as shown in **Figure 11.2**. (credit: modification of work by Voyager Project, JPL, and NASA)

Different gases freeze at different temperatures. At the temperatures and pressures of the upper atmospheres of Jupiter and Saturn, methane remains a gas, but ammonia can condense and freeze. (Similarly, water vapor condenses high in Earth's atmosphere to produce clouds of ice crystals.) The primary clouds that we see around these planets, whether from a spacecraft or through a telescope, are composed of frozen ammonia crystals. The ammonia clouds mark the upper edge of the planets' tropospheres; above that is the stratosphere, the coldest part of the atmosphere. (These layers were initially defined in **Earth as a Planet**.)

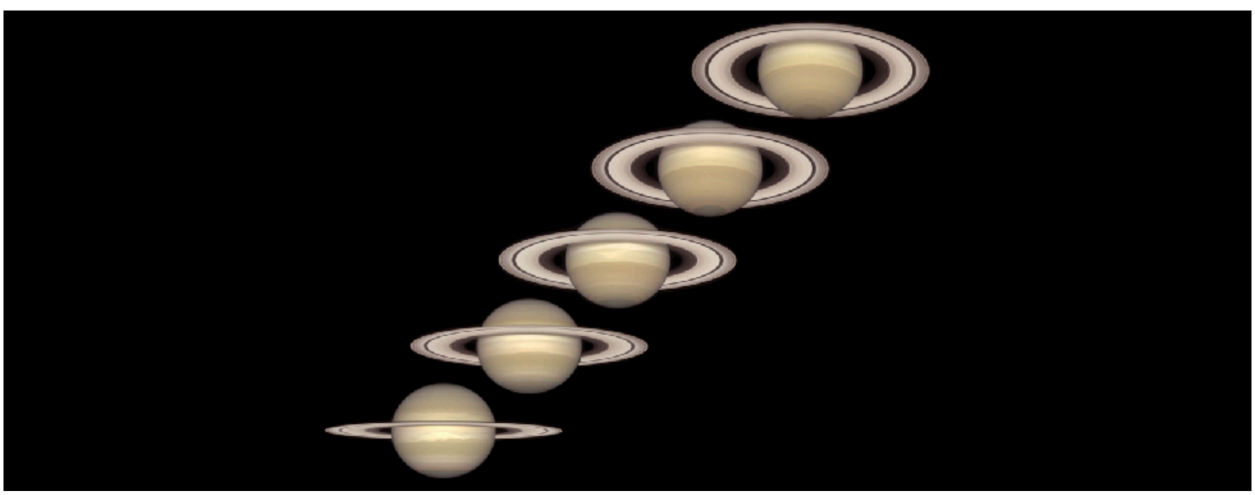


Figure 11.11 Saturn over Five Years. These beautiful images of Saturn were recorded by the Hubble Space Telescope between 1996 and 2000. Since Saturn is tilted by 27°, we see the orientation of Saturn's rings around its equator change as the planet moves along its orbit. Note the horizontal bands in the atmosphere. (credit: modification of work by NASA and The Hubble Heritage Team (STScI/AURA))

The diagrams in **Figure 11.12** show the structure and clouds in the atmospheres of all four jovian planets. On both Jupiter and Saturn, the temperature near the cloud tops is about 140 K (only a little cooler than the polar caps of Mars). On Jupiter, this cloud level is at a pressure of about 0.1 bar (one tenth the atmospheric pressure at the surface of Earth), but on Saturn it occurs lower in the atmosphere, at about 1 bar. Because the ammonia clouds lie so much deeper on Saturn, they are more difficult to see, and the overall appearance of the planet is much blander than is Jupiter's appearance.

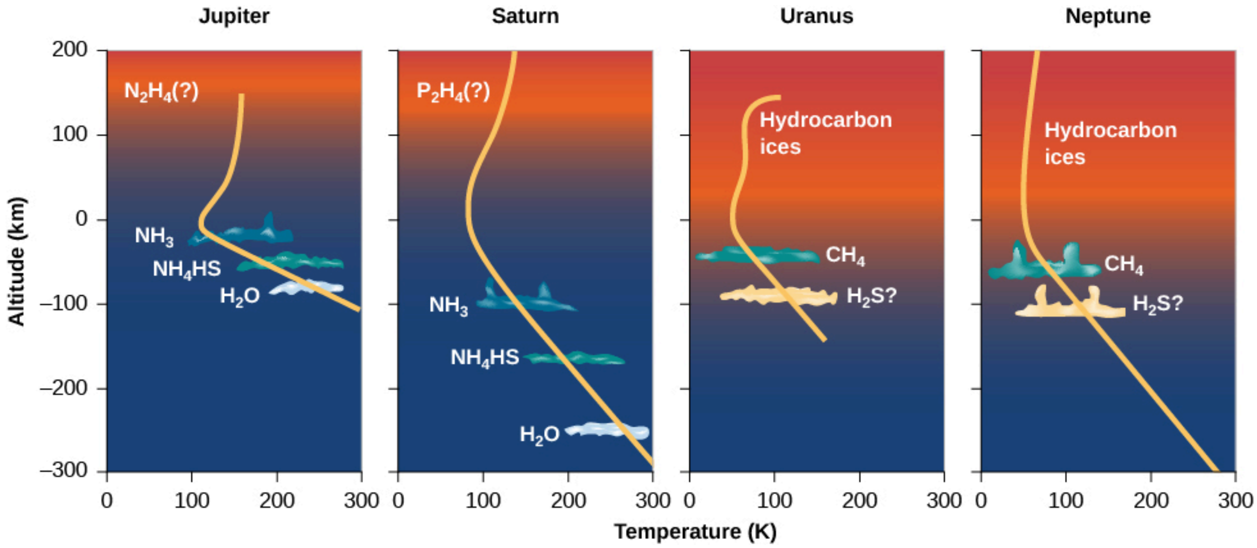


Figure 11.12 Atmospheric Structure of the Jovian Planets. In each diagram, the yellow line shows how the temperature (see the scale on the bottom) changes with altitude (see the scale at the left). The location of the main layers on each planet is also shown.

Within the tropospheres of these planets, the temperature and pressure both increase with depth. Through breaks in the ammonia clouds, we can see tantalizing glimpses of other cloud layers that can form in these deeper regions of the atmosphere—regions that were sampled directly for Jupiter by the Galileo probe that fell into the planet.

As it descended to a pressure of 5 bars, the probe should have passed into a region of frozen water clouds, then below that into clouds of liquid water droplets, perhaps similar to the common clouds of the terrestrial troposphere. At least this is what scientists expected. But the probe saw no water clouds, and it measured a surprisingly low abundance of water vapor in the atmosphere. It soon became clear to the Galileo scientists that the probe happened to descend through an unusually dry, cloud-free region of the atmosphere—a giant downdraft of cool, dry gas. Andrew Ingersoll of Caltech, a member of the Galileo team, called this entry site the "desert" of Jupiter. It's a pity that the probe did not enter a more representative region, but that's the luck of the cosmic draw. The probe continued to make measurements to a pressure of 22 bars but found no other cloud layers before its instruments stopped working. It also detected lightning storms, but only at great distances, further suggesting that the probe itself was in a region of clear weather.

Above the visible ammonia clouds in Jupiter's atmosphere, we find the clear stratosphere, which reaches a minimum temperature near 120 K. At still higher altitudes, temperatures rise again, just as they do in the upper atmosphere of Earth, because here the molecules absorb ultraviolet light from the Sun. The cloud colors are due to impurities, the product of chemical reactions among the atmospheric gases in a process we call **photochemistry**. In Jupiter's upper atmosphere, photochemical reactions create a variety of fairly complex compounds of hydrogen and carbon that form a thin layer of smog far above the visible clouds. We show this smog as a fuzzy orange region in Figure 11.12; however, this thin layer does not block our view of the clouds beneath it.

The visible atmosphere of Saturn is composed of approximately 75% hydrogen and 25% helium, with trace amounts of methane, ethane, propane, and other hydrocarbons. The overall structure is similar to that of Jupiter. Temperatures are somewhat colder, however, and the atmosphere is more extended due to Saturn's lower surface gravity. Thus, the layers are stretched out over a longer distance, as you can see in Figure 11.12. Overall, though, the same atmospheric regions, condensation cloud, and photochemical reactions that we see on Jupiter should be present on Saturn (Figure 11.13).

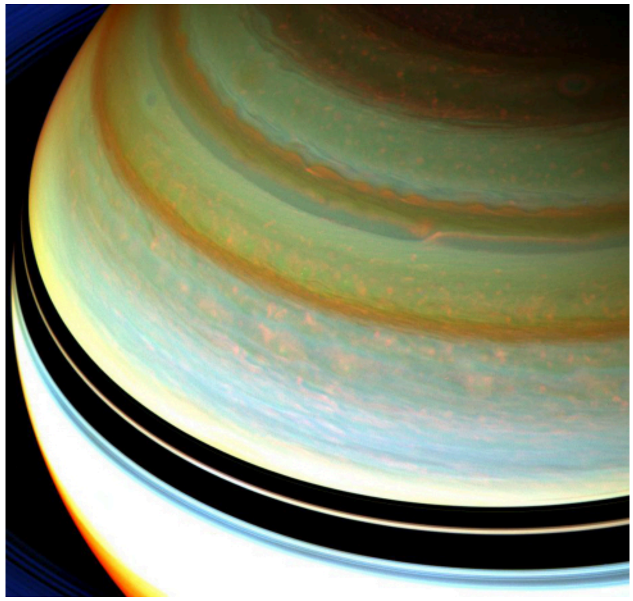


Figure 11.13 Cloud Structure on Saturn. In this Cassini image, colors have been intensified, so we can see the bands and zones and storms in the atmosphere. The dark band is the shadow of the rings on the planet. (credit: NASA/JPL-Caltech/Space Science Institute)

Saturn has one anomalous cloud structure that has mystified scientists: a hexagonal wave pattern around the north pole, shown in Figure 11.14. The six sides of the hexagon are each longer than the diameter of Earth. Winds are also extremely high on Saturn, with speeds of up to 1800 kilometers per hour measured near the equator.

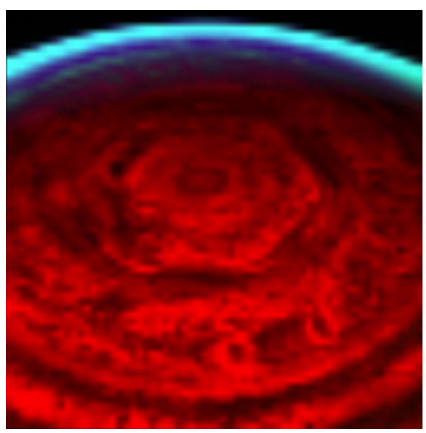


Figure 11.14 Hexagon Pattern on Saturn’s North Pole. In this infrared nighttime image from the Cassini mission, the path of Saturn’s hexagonal jet stream is visible as the planet’s north pole emerges from the darkness of winter. (credit: NASA/JPL/University of Arizona)

LINK TO LEARNING

See images of Saturn’s hexagon (https://openstax.org/l/30Hexagon) with exaggerated color in this brief NASA video.

Unlike Jupiter and Saturn, Uranus is almost entirely featureless as seen at wavelengths that range from the ultraviolet to the infrared (see its rather boring image in **Figure 11.1**). Calculations indicate that the basic atmospheric structure of Uranus should resemble that of Jupiter and Saturn, although its upper clouds (at the 1-bar pressure level) are composed of methane rather than ammonia. However, the absence of an internal heat source suppresses up-and-down movement and leads to a very stable atmosphere with little visible structure.

Neptune differs from Uranus in its appearance, although their basic atmospheric temperatures are similar. The upper clouds are composed of methane, which forms a thin cloud layer near the top of the troposphere at a temperature of 70 K and a pressure of 1.5 bars. Most the atmosphere above this level is clear and transparent, with less haze than is found on Uranus. The scattering of sunlight by gas molecules lends Neptune a pale blue color similar to that of Earth’s atmosphere (**Figure 11.15**). Another cloud layer, perhaps composed of hydrogen sulfide ice particles, exists below the methane clouds at a pressure of 3 bars.

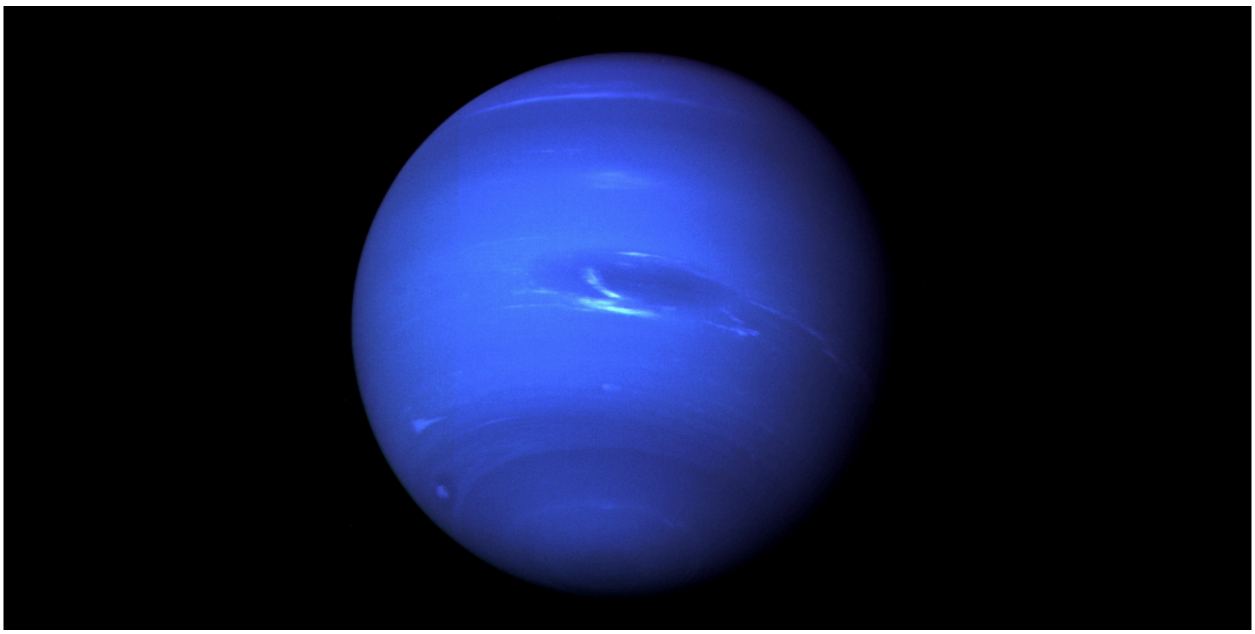


Figure 11.15 Neptune. The planet Neptune is seen here as photographed by Voyager in 1989. The blue color, exaggerated with computer processing, is caused by the scattering of sunlight in the planet’s upper atmosphere. (credit: modification of work by NASA)

Unlike Uranus, Neptune has an atmosphere in which convection currents—vertical drafts of gas—emanate from the interior, powered by the planet’s internal heat source. These currents carry warm gas above the 1.5-bar cloud level, forming additional clouds at elevations about 75 kilometers higher. These high-altitude clouds form bright white patterns against the blue planet beneath. Voyager photographed distinct shadows on the methane cloud tops, permitting the altitudes of the high clouds to be calculated. **Figure 11.16** is a remarkable close-up of Neptune’s outer layers that could never have been obtained from Earth.

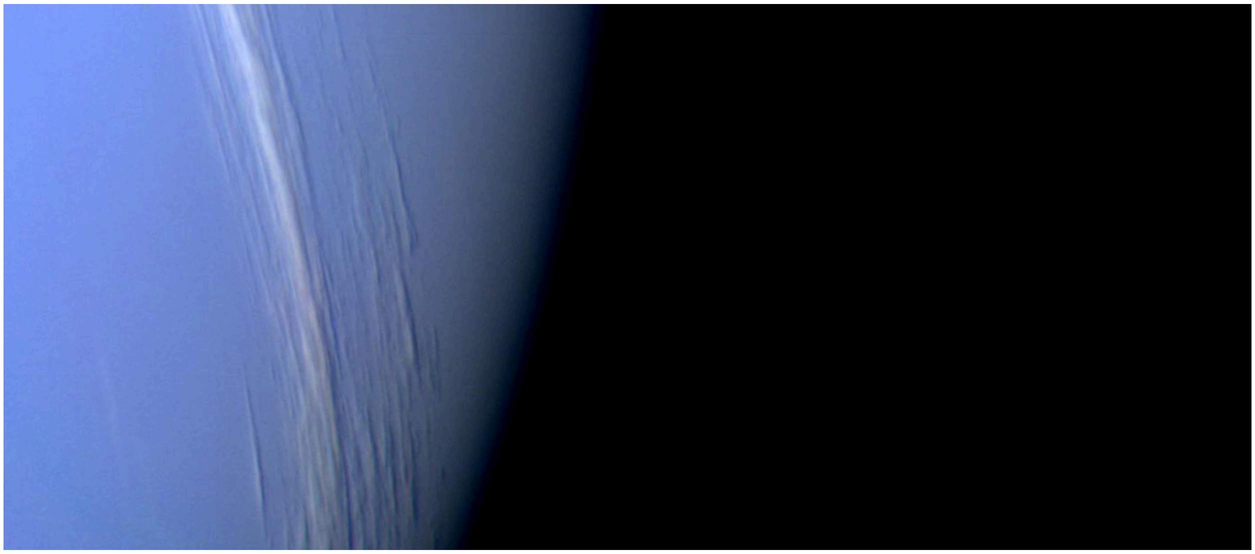


Figure 11.16 High Clouds in the Atmosphere of Neptune. These bright, narrow cirrus clouds are made of methane ice crystals. From the shadows they cast on the thicker cloud layer below, we can measure that they are about 75 kilometers higher than the main clouds. (credit: modification of work by NASA/JPL)

Winds and Weather

The atmospheres of the jovian planets have many regions of high pressure (where there is more air) and low pressure (where there is less). Just as it does on Earth, air flows between these regions, setting up wind patterns that are then distorted by the rotation of the planet. By observing the changing cloud patterns on the jovian planets, we can measure wind speeds and track the circulation of their atmospheres.

The atmospheric motions we see on these planets are fundamentally different from those on the terrestrial planets. The giants spin faster, and their rapid rotation tends to smear out of the circulation into horizontal (east-west) patterns parallel to the equator. In addition, there is no solid surface below the atmosphere against which the circulation patterns can rub and lose energy (which is how tropical storms on Earth ultimately die out when they come over land).

As we have seen, on all the giants except Uranus, heat from the inside contributes about as much energy to the atmosphere as sunlight from the outside. This means that deep convection currents of rising hot air and falling cooler air circulate throughout the atmospheres of the planets in the vertical direction.

The main features of Jupiter’s visible clouds (see **Figure 11.2** and **Figure 11.10**, for example) are alternating dark and light bands that stretch around the planet parallel to the equator. These bands are semi-permanent features, although they shift in intensity and position from year to year. Consistent with the small tilt of Jupiter’s axis, the pattern does not change with the seasons.

More fundamental than these bands are underlying east-west wind patterns in the atmosphere, which do not appear to change at all, even over many decades. These are illustrated in **Figure 11.17**, which indicates how strong the winds are at each latitude for the giant planets. At Jupiter’s equator, a jet stream flows eastward with a speed of about 90 meters per second (300 kilometers per hour), similar to the speed of jet streams in Earth’s upper atmosphere. At higher latitudes there are alternating east- and west-moving streams, with each hemisphere an almost perfect mirror image of the other. Saturn shows a similar pattern, but with a much stronger equatorial jet stream, as we noted earlier.

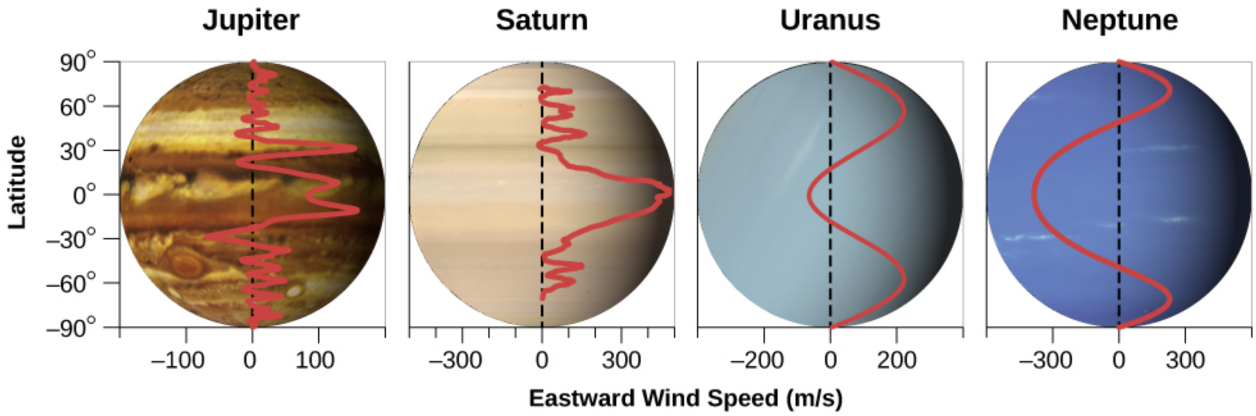


Figure 11.17 Winds on the Giant Planets. This image compares the winds of the giant planets, illustrating that wind speed (shown on the horizontal axis) and wind direction vary with latitude (shown on the vertical axis). Winds are measured relative to a planet's internal rotation speed. A positive velocity means that the winds are blowing in the same direction as, but faster than, the planet's internal rotation. A negative velocity means that the winds are blowing more slowly than the planet's internal rotation. Note that Saturn's winds move faster than those of the other planets.

The light zones on Jupiter are regions of upwelling air capped by white ammonia cirrus clouds. They apparently represent the tops of upward-moving convection currents.[2] The darker belts are regions where the cooler atmosphere moves downward, completing the convection cycle; they are darker because fewer ammonia clouds mean we can see deeper into the atmosphere, perhaps down to a region of ammonium hydrosulfide (NH_4SH) clouds. The Galileo probe sampled one of the clearest of these dry downdrafts.

In spite of the strange seasons induced by the 98° tilt of its axis, Uranus' basic circulation is parallel with its equator, as is the case on Jupiter and Saturn. The mass of the atmosphere and its capacity to store heat are so great that the alternating 42-year periods of sunlight and darkness have little effect. In fact, Voyager measurements show that the atmospheric temperature is even a few degrees higher on the dark winter side than on the hemisphere facing the Sun. This is another indication that the behavior of such giant planet atmospheres is a complex problem that we do not fully understand.

Neptune's weather is characterized by strong east-west winds generally similar to those observed on Jupiter and Saturn. The highest wind speeds near its equator reach 2100 kilometers per hour, even higher than the peak winds on Saturn. The Neptune equatorial jet stream actually approaches supersonic speeds (faster than the speed of sound in Neptune's air).

Giant Storms on Giant Planets

Superimposed on the regular atmospheric circulation patterns we have just described are many local disturbances—weather systems or *storms*, to borrow the term we use on Earth. The most prominent of these are large, oval-shaped, high-pressure regions on both Jupiter (Figure 11.18) and Neptune.

2 Recall from earlier chapters that convection is a process in which liquids, heated from underneath, have regions where hot material rises and cooler material descends. You can see convection at work if you heat oatmeal on a stovetop or watch miso soup boil.

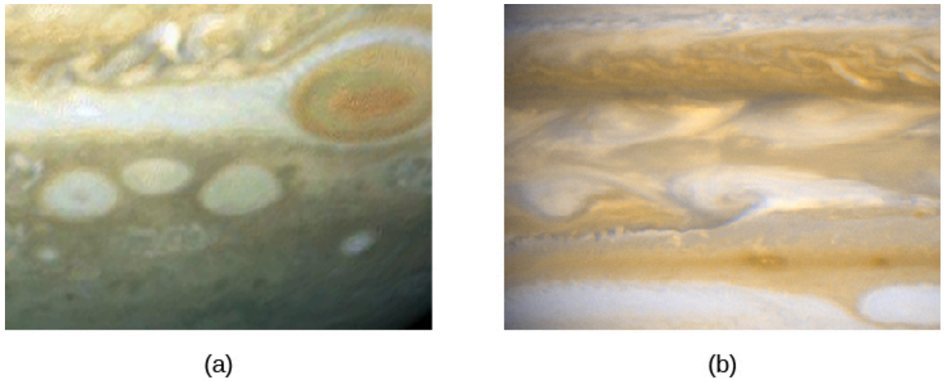


Figure 11.18 Storms on Jupiter. Two examples of storms on Jupiter illustrate the use of enhanced color and contrast to bring out faint features. (a) The three oval-shaped white storms below and to the left of Jupiter's Great Red Spot are highly active, and moved closer together over the course of seven months between 1994 and 1995. (b) The clouds of Jupiter are turbulent and ever-changing, as shown in this Hubble Space Telescope image from 2007. (credit a: modification of work by Reta Beebe, Amy Simon (New Mexico State Univ.), and NASA; credit b: modification of work by NASA, ESA, and A. Simon-Miller (NASA Goddard Space Flight Center))

The largest and most famous of Jupiter's storms is the Great Red Spot, a reddish oval in the southern hemisphere that changes slowly; it was 25,000 kilometers long when Voyager arrived in 1979, but it had shrunk to 20,000 kilometers by the end of the Galileo mission in 2000 (**Figure 11.19**). The giant storm has persisted in Jupiter's atmosphere ever since astronomers were first able to observe it after the invention of the telescope, more than 300 years ago. However, it has continued to shrink, raising speculation that we may see its end within a few decades.

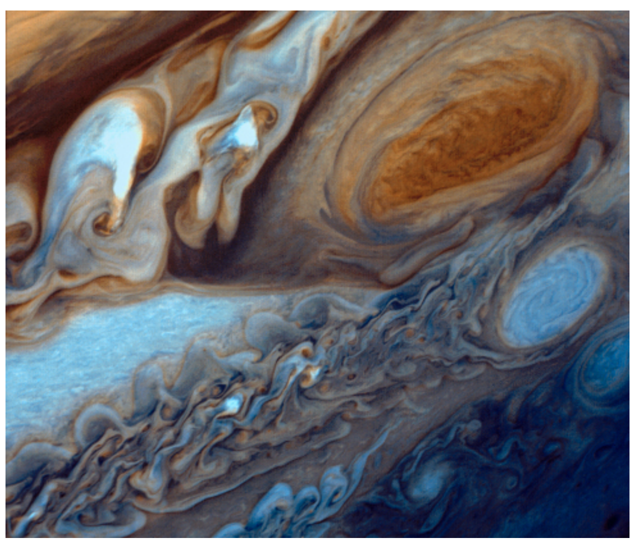


Figure 11.19 Jupiter's Great Red Spot. This is the largest storm system on Jupiter, as seen during the Voyager spacecraft flyby. Below and to the right of the Red Spot is one of the white ovals, which are similar but smaller high-pressure features. The white oval is roughly the size of planet Earth, to give you a sense of the huge scale of the weather patterns we are seeing. The colors on the Jupiter image have been somewhat exaggerated here so astronomers (and astronomy students) can study their differences more effectively. See **Figure 11.2** to get a better sense of the colors your eye would actually see near Jupiter. (credit: NASA/JPL)

In addition to its longevity, the Red Spot differs from terrestrial storms in being a high-pressure region; on our planet, such storms are regions of lower pressure. The Red Spot's counterclockwise rotation has a period of six days. Three similar but smaller disturbances (about as big as Earth) formed on Jupiter in the 1930s. They look like white ovals, and one can be seen clearly below and to the right of the Great Red Spot in **Figure 11.19**. In 1998, the Galileo spacecraft watched as two of these ovals collided and merged into one.

We don't know what causes the Great Red Spot or the white ovals, but we do have an idea how they can last so long once they form. On Earth, the lifetime of a large oceanic hurricane or typhoon is typically a few weeks, or even less when it moves over the continents and encounters friction with the land. Jupiter has no solid surface to slow down an atmospheric disturbance; furthermore, the sheer size of the disturbances lends them stability. We can calculate that on a planet with no solid surface, the lifetime of anything as large as the Red Spot should be measured in centuries, while lifetimes for the white ovals should be measured in decades, which is pretty much what we have observed.

Despite Neptune's smaller size and different cloud composition, Voyager showed that it had an atmospheric feature surprisingly similar to Jupiter's Great Red Spot. Neptune's Great Dark Spot was nearly 10,000 kilometers long (**Figure 11.15**). On both planets, the giant storms formed at latitude 20° S, had the same shape, and took up about the same fraction of the planet's diameter. The Great Dark Spot rotated with a period of 17 days, versus about 6 days for the Great Red Spot. When the Hubble Space Telescope examined Neptune in the mid-1990s, however, astronomers could find no trace of the Great Dark Spot on their images.

Although many of the details of the weather on the jovian planets are not yet understood, it is clear that if you are a fan of dramatic weather, these worlds are the place to look. We study the features in these atmospheres not only for what they have to teach us about conditions in the jovian planets, but also because we hope they can help us understand the weather on Earth just a bit better.

EXAMPLE 11.1

Storms and Winds

The wind speeds in circular storm systems can be formidable on both Earth and the giant planets. Think about our big terrestrial hurricanes. If you watch their behavior in satellite images shown on weather outlets, you will see that they require about one day to rotate. If a storm has a diameter of 400 km and rotates once in 24 h, what is the wind speed?

Solution

Speed equals distance divided by time. The distance in this case is the circumference ($2\pi R$ or πd), or approximately 1250 km, and the time is 24 h, so the speed at the edge of the storm would be about 52 km/h. Toward the center of the storm, the wind speeds can be much higher.

Check Your Learning

Jupiter's Great Red Spot rotates in 6 d and has a circumference equivalent to a circle with radius 10,000 km. Calculate the wind speed at the outer edge of the spot.

Answer:

For the Great Red Spot of Jupiter, the circumference ($2\pi R$) is about 63,000 km. Six d equals 144 h, suggesting a speed of about 436 km/h. This is much faster than wind speeds on Earth.

CHAPTER 11 REVIEW

KEY TERMS

photochemistry chemical changes caused by electromagnetic radiation

synchrotron radiation the radiation emitted by charged particles being accelerated in magnetic fields and moving at speeds near that of light

SUMMARY

11.1 Exploring the Outer Planets

The outer solar system contains the four giant planets: Jupiter, Saturn, Uranus, and Neptune. The gas giants Jupiter and Saturn have overall compositions similar to that of the Sun. These planets have been explored by the Pioneer, Voyager, Galileo, and Cassini spacecraft. Voyager 2, perhaps the most successful of all space-science missions, explored Jupiter (1979), Saturn (1981), Uranus (1986), and Neptune (1989)—a grand tour of the giant planets—and these flybys have been the only explorations to date of the ice giants Uranus and Neptune. The Galileo and Cassini missions were long-lived orbiters, and each also deployed an entry probe, one into Jupiter and one into Saturn's moon Titan.

11.2 The Giant Planets

Jupiter is 318 times more massive than Earth. Saturn is about 25% as massive as Jupiter, and Uranus and Neptune are only 5% as massive. All four have deep atmospheres and opaque clouds, and all rotate quickly with periods from 10 to 17 hours. Jupiter and Saturn have extensive mantles of liquid hydrogen. Uranus and Neptune are depleted in hydrogen and helium relative to Jupiter and Saturn (and the Sun). Each giant planet has a core of "ice" and "rock" of about 10 Earth masses. Jupiter, Saturn, and Neptune have major internal heat sources, obtaining as much (or more) energy from their interiors as by radiation from the Sun. Uranus has no measurable internal heat. Jupiter has the strongest magnetic field and largest magnetosphere of any planet, first discovered by radio astronomers from observations of synchrotron radiation.

11.3 Atmospheres of the Giant Planets

The four giant planets have generally similar atmospheres, composed mostly of hydrogen and helium. Their atmospheres contain small quantities of methane and ammonia gas, both of which also condense to form clouds. Deeper (invisible) cloud layers consist of water and possibly ammonium hydrosulfide (Jupiter and Saturn) and hydrogen sulfide (Neptune). In the upper atmospheres, hydrocarbons and other trace compounds are produced by photochemistry. We do not know exactly what causes the colors in the clouds of Jupiter. Atmospheric motions on the giant planets are dominated by east-west circulation. Jupiter displays the most active cloud patterns, with Neptune second. Saturn is generally bland, in spite of its extremely high wind speeds, and Uranus is featureless (perhaps due to its lack of an internal heat source). Large storms (oval-shaped high-pressure systems such as the Great Red Spot on Jupiter and the Great Dark Spot on Neptune) can be found in some of the planet atmospheres.

FOR FURTHER EXPLORATION

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Uranus and Neptune

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Gore, R. “Neptune: Voyager’s Last Picture Show.” *National Geographic* (August 1990): 35.

Lunine, J. “Neptune at 150.” *Sky & Telescope* (September 1996): 38. Nice review.

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Jupiter

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Nine Planets Site: **http://nineplanets.org/jupiter.html (http://nineplanets.org/jupiter.html)**

Planetary Sciences Site: **http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html (http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html)**

Saturn

NASA Solar System Exploration: **http://Solarsystem.nasa.gov/planets/saturn (http://Solarsystem.nasa.gov/planets/saturn)**

Nine Planets Site: http://nineplanets.org/saturn.html (http://nineplanets.org/saturn.html)

Planetary Sciences Site: http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html (http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html)

Uranus

NASA Solar System Exploration: http://Solarsystem.nasa.gov/planets/uranus (http://Solarsystem.nasa.gov/planets/uranus)

Nine Planets Site: http://nineplanets.org/uranus.html (http://nineplanets.org/uranus.html)

Planetary Sciences Site: http://nssdc.gsfc.nasa.gov/planetary/planets/uranuspage.html (http://nssdc.gsfc.nasa.gov/planetary/planets/uranuspage.html)

Neptune

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Nine Planets Site: http://nineplanets.org/neptune.html (http://nineplanets.org/neptune.html)

Planetary Sciences Site: http://nssdc.gsfc.nasa.gov/planetary/planets/neptunepage.html (http://nssdc.gsfc.nasa.gov/planetary/planets/neptunepage.html)

Missions

Cassini Mission Site at the Jet Propulsion Lab: http://saturn.jpl.nasa.gov/index.cfm (http://saturn.jpl.nasa.gov/index.cfm)

Cassini-Huygens Mission Site at European Space Agency: http://sci.esa.int/cassini-huygens/ (http://sci.esa.int/cassini-huygens/)

NASA Galileo Mission Site: http://Solarsystem.nasa.gov/galileo/ (http://Solarsystem.nasa.gov/galileo/)

NASA's Juno Mission to Jupiter: http://www.nasa.gov/mission_pages/juno/main/index.html (http://www.nasa.gov/mission_pages/juno/main/index.html)

Voyager Mission Site at the Jet Propulsion Lab: http://voyager.jpl.nasa.gov/ (http://voyager.jpl.nasa.gov/)

Videos

Cassini: 15 Years of Exploration: https://www.youtube.com/watch?v=2z8fzz_MBAw (https://www.youtube.com/watch?v=2z8fzz_MBAw) . Quick visual summary of mission highlights (2:29).

In the Land of Enchantment: The Epic Story of the Cassini Mission to Saturn: https://www.youtube.com/watch?v=Vx135n8VFxY (https://www.youtube.com/watch?v=Vx135n8VFxY) . An inspiring illustrated lecture by Cassini Mission Imagining Lead Scientist Carolyn Porco (1:37:52).

Jupiter: The Largest Planet: http://www.youtube.com/watch?v=s56pxa9lpvo (http://www.youtube.com/watch?v=s56pxa9lpvo) . Produced by NASA's Goddard Space Flight Center and Science on a Sphere (7:29).

COLLABORATIVE GROUP ACTIVITIES

A. A new member of Congress has asked your group to investigate why the Galileo probe launched into the Jupiter atmosphere in 1995 survived only 57 minutes and whether this was an example of a terrible scandal. Make a list of all the reasons the probe did not last longer, and why it was not made more durable.

(Remember that the probe had to hitch a ride to Jupiter!)

B. Select one of the jovian planets and organize your group to write a script for an evening news weather report for the planet you chose. Be sure you specify roughly how high in the atmosphere the region lies for which you are giving the report.

C. What does your group think should be the next step to learn more about the giant planets? Put cost considerations aside for a moment: What kind of mission would you recommend to NASA to learn more about these giant worlds? Which world or worlds should get the highest priority and why?

D. Suppose that an extremely dedicated (and slightly crazy) astronomer volunteers to become a human probe into Jupiter (and somehow manages to survive the trip through Jupiter's magnetosphere alive). As she enters the upper atmosphere of Jupiter, would she fall faster or slower than she would fall doing the same suicidal jump into the atmosphere of solid Earth? Groups that have some algebra background could even calculate the force she would feel compared to the force on Earth. (Bonus question: If she were in a capsule, falling into Jupiter feet first, and the floor of the capsule had a scale, what would the scale show as her weight compared to her weight on Earth?)

E. Would you or anyone in your group volunteer for a one-way, life-long mission to a space station orbiting any of the gas giants without ever being able to return to Earth? What are the challenges of such a mission? Should we leave all exploration of the outer solar system to unmanned space probes?

EXERCISES

Review Questions

1. What are the main challenges involved in sending probes to the giant planets?

2. Why is it difficult to drop a probe like Galileo? How did engineers solve this problem?

3. Explain why visual observation of the gas giants is not sufficient to determine their rotation periods, and what evidence was used to deduce the correct periods.

4. What are the seasons like on Jupiter?

5. What is the consequence of Uranus' spin axis being 98° away from perpendicular to its orbital plane?

6. Describe the seasons on the planet Uranus.

7. At the pressures in Jupiter's interior, describe the physical state of the hydrogen found there.

8. Which of the gas giants has the largest icy/rocky core compared to its overall size?

9. In the context of the giant planets and the conditions in their interiors, what is meant by "rock" and "ice"?

10. What is the primary source of Jupiter's internal heat?

11. Describe the interior heat source of Saturn.

12. Which planet has the strongest magnetic field, and hence the largest magnetosphere? What is its source?

13. What are the visible clouds on the four giant planets composed of, and why are they different from each other?

14. Compare the atmospheric circulation (weather) of the four giant planets.

15. What are the main atmospheric heat sources of each of the giant planets?

16. Why do the upper levels of Neptune's atmosphere appear blue?

17. How do storms on Jupiter differ from storm systems on Earth?

Thought Questions

18. Describe the differences in the chemical makeup of the inner and outer parts of the solar system. What is the relationship between what the planets are made of and the temperature where they formed?

19. How did the giant planets grow to be so large?

20. Jupiter is denser than water, yet composed for the most part of two light gases, hydrogen and helium. What makes Jupiter as dense as it is?

21. Would you expect to find free oxygen gas in the atmospheres of the giant planets? Why or why not?

22. Why would a tourist brochure (of the future) describing the most dramatic natural sights of the giant planets have to be revised more often than one for the terrestrial planets?

23. The water clouds believed to be present on Jupiter and Saturn exist at temperatures and pressures similar to those in the clouds of the terrestrial atmosphere. What would it be like to visit such a location on Jupiter or Saturn? In what ways would the environment differ from that in the clouds of Earth?

24. Describe the different processes that lead to substantial internal heat sources for Jupiter and Saturn. Since these two objects generate much of their energy internally, should they be called stars instead of planets? Justify your answer.

25. Research the Galileo mission. What technical problems occurred between the mission launch and the arrival of the craft in Jupiter's system, and how did the mission engineers deal with them? (Good sources of information include *Astronomy* and *Sky & Telescope* articles, plus the mission website.)

Figuring For Yourself

26. How many times more pressure exists in the interior of Jupiter compared to that of Earth?

27. Calculate the wind speed at the edge of Neptune's Great Dark Spot, which was 10,000 km in diameter and rotated in 17 d.

28. Calculate how many Earths would fit into the volumes of Saturn, Uranus, and Neptune.

29. As the Voyager spacecraft penetrated into the outer solar system, the illumination from the Sun declined. Relative to the situation at Earth, how bright is the sunlight at each of the jovian planets?

30. The ions in the inner parts of Jupiter's magnetosphere rotate with the same period as Jupiter. Calculate how fast they are moving at the orbit of Jupiter's moon Io (see **Appendix G**). Will these ions strike Io from behind or in front as it moves about Jupiter?

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

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:

- Name the major moons of 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.

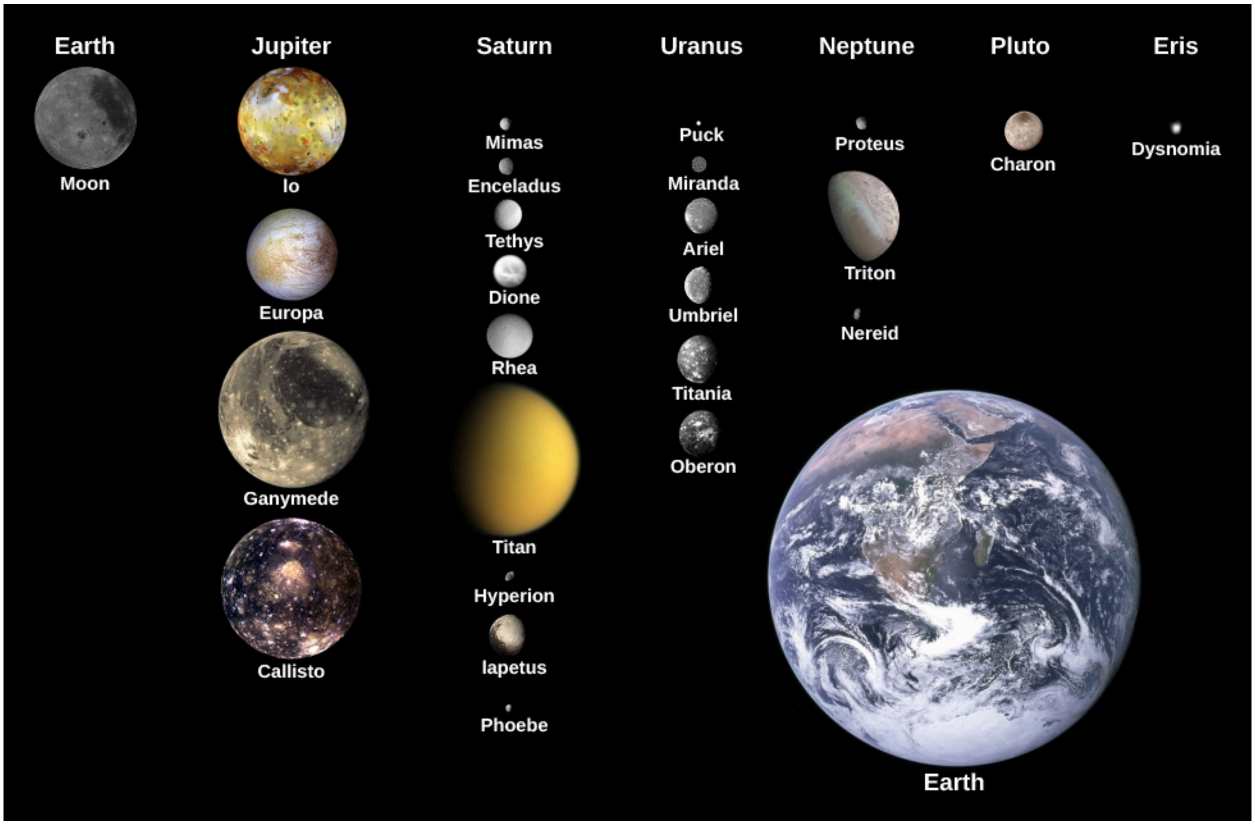


Figure 12.2 Moons of the Solar System. This image shows some selected moons of our solar system and their comparison to the size of Earth's Moon and Earth itself. (credit: modification of work by NASA)

The Jupiter System

Jupiter has 67 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 62 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. (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^3)	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).

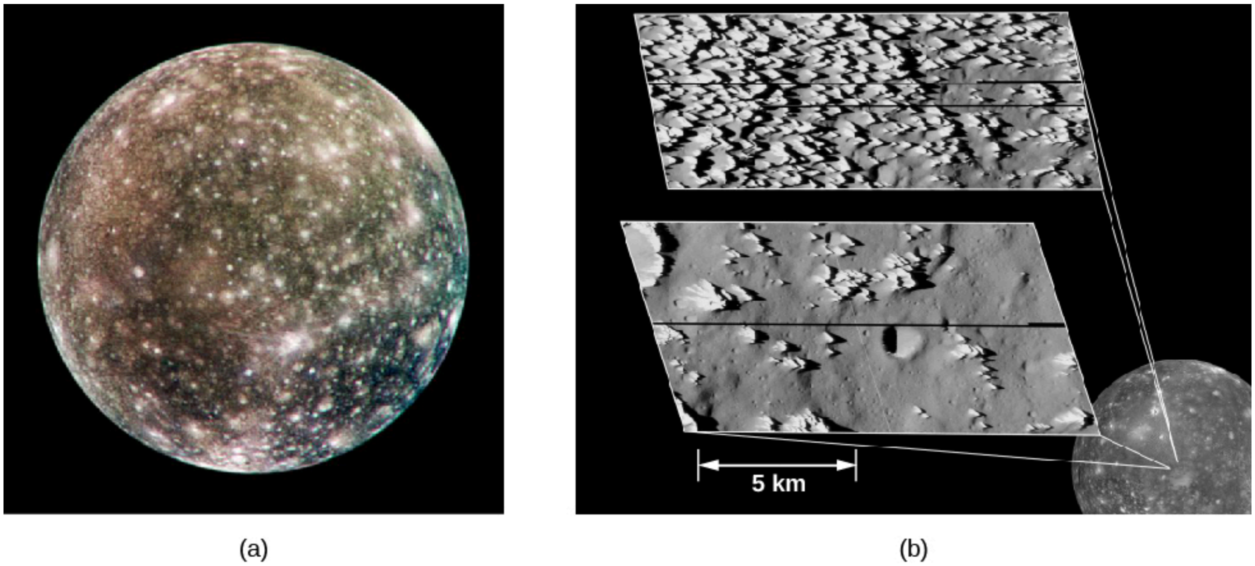


Figure 12.3 Callisto. (a) Jupiter's outermost large moon shows a heavily cratered surface. Astronomers believe that the bright areas are mostly ice, while the darker areas are more eroded, ice-poor material. (b) These high-resolution images, taken by NASA's Galileo spacecraft in May 2001, show the icy 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.

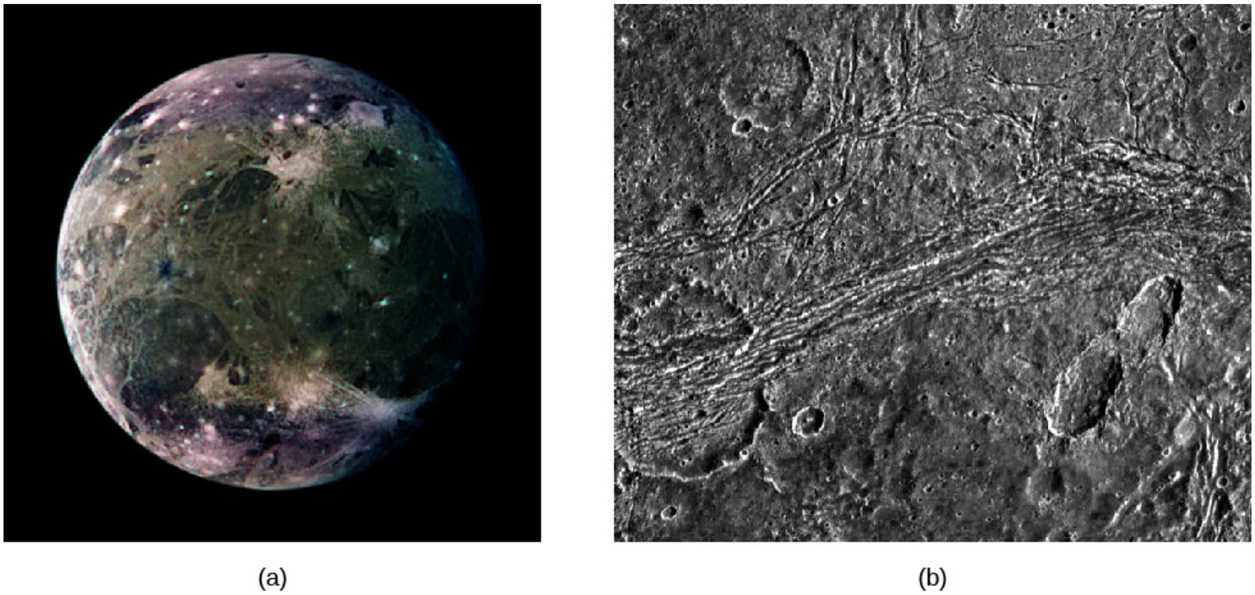


Figure 12.4 Ganymede. (a) This global view of Ganymede, the largest moon in the solar system, was taken by Voyager 2. The colors are enhanced to make spotting differences easier. Darker places are older, more heavily cratered regions; the lighter areas are younger (the reverse of our Moon). The brightest 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.

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**).

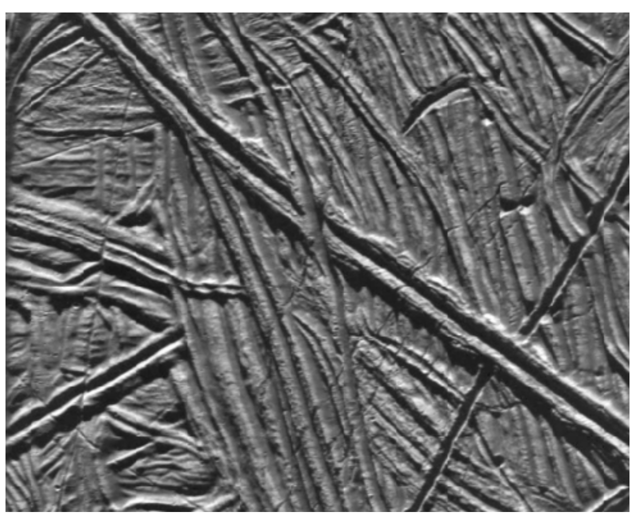


Figure 12.6 Very High-Resolution Galileo Image of One Young Double Ridge on Europa. The area in this picture is only 15 kilometers across. It appears to have formed when viscous icy material was forced up through a long, straight crack in the crust. Note how the young ridge going from top left toward 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.[1] 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)** 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)** 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. In planning a future mission, it may be possible to include a small lander craft as well.

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.

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

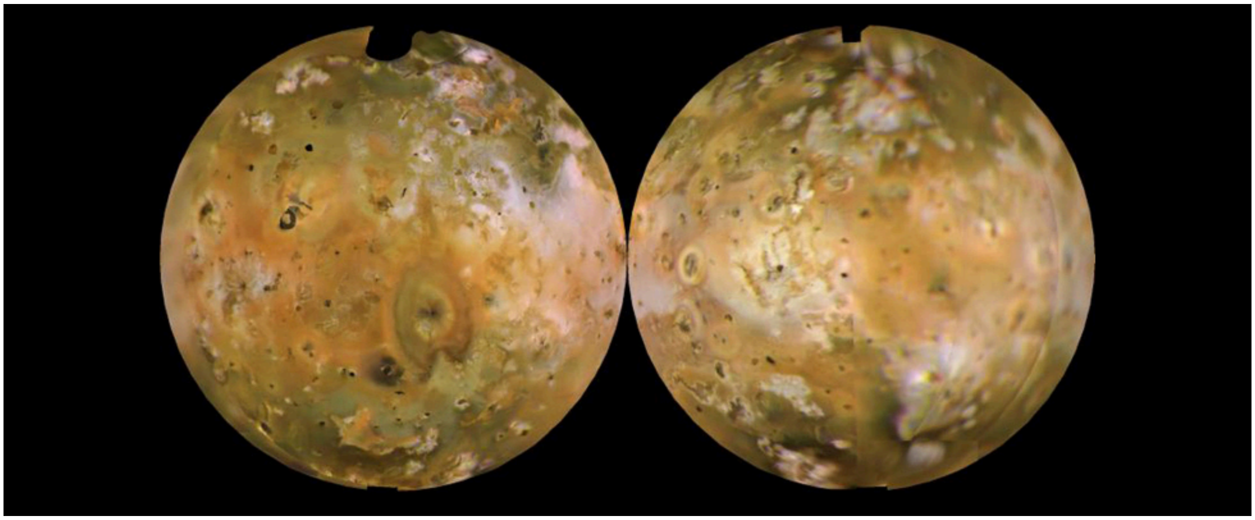


Figure 12.7 Two Sides of Io. This composite image shows both sides of the volcanically active moon Io. The orange deposits are sulfur snow; the white is sulfur dioxide. (Carl Sagan once quipped that Io looks as if it desperately needs a shot of penicillin.) (credit: modification of work by NASA/JPL/USGS)

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).

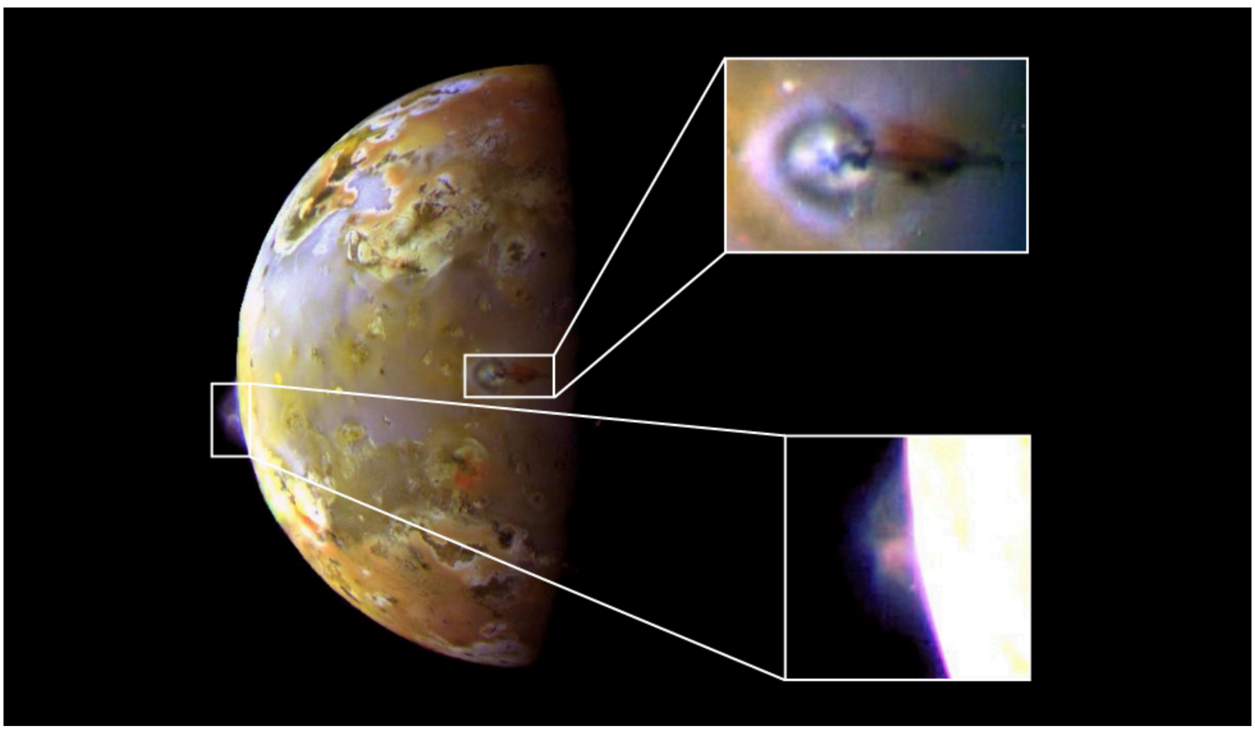


Figure 12.8 Volcanic Eruptions on Io. This composite image from NASA’s Galileo spacecraft shows close-ups (the two inset photos) of two separate volcanic eruptions on Jupiter’s volcanic moon, Io. In the upper inset image, you can see a close up of a bluish plume rising about 140 kilometers above the 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)** 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**.

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).

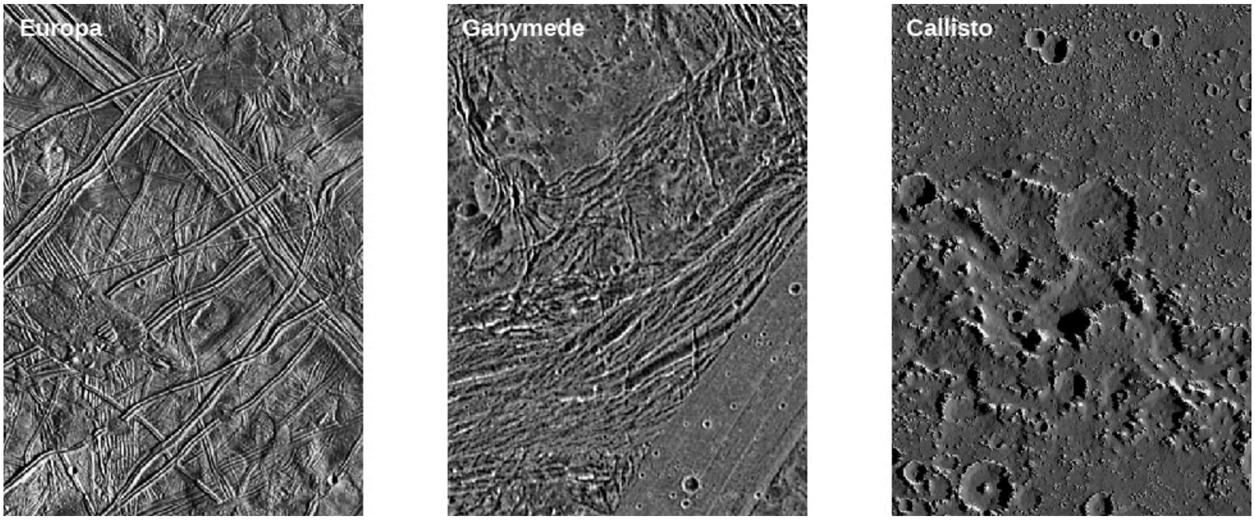


Figure 12.11 Three Icy Moons. These Galileo images compare the surfaces of Europa, Ganymede, and Callisto at the same resolution. Note that the number of craters (and thus the age of the surface we see) increases as we go from Europa to Ganymede to Callisto. The Europa image is one of those where the 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).

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_4), ethane (C_2H_6), and propane (C_3H_8), and nitrogen compounds such as hydrogen cyanide (HCN), cyanogen (C_2N_2), and cyanoacetylene (HC_3N). 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**.

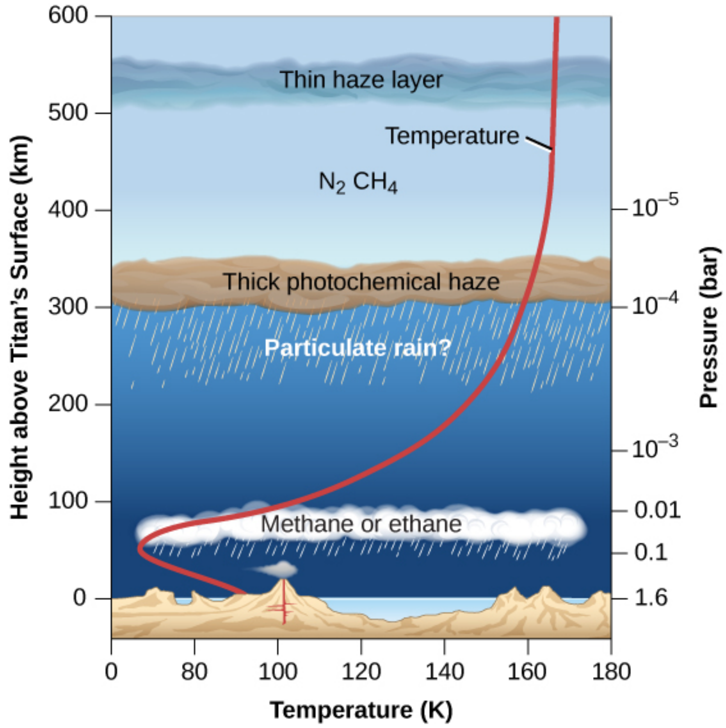


Figure 12.12 Structure of Titan's Atmosphere. Some characteristics of Titan's atmosphere resemble those of Earth's atmosphere, although it is much colder than our planet. The red line indicates the temperature of Titan's atmosphere at different altitudes.

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.

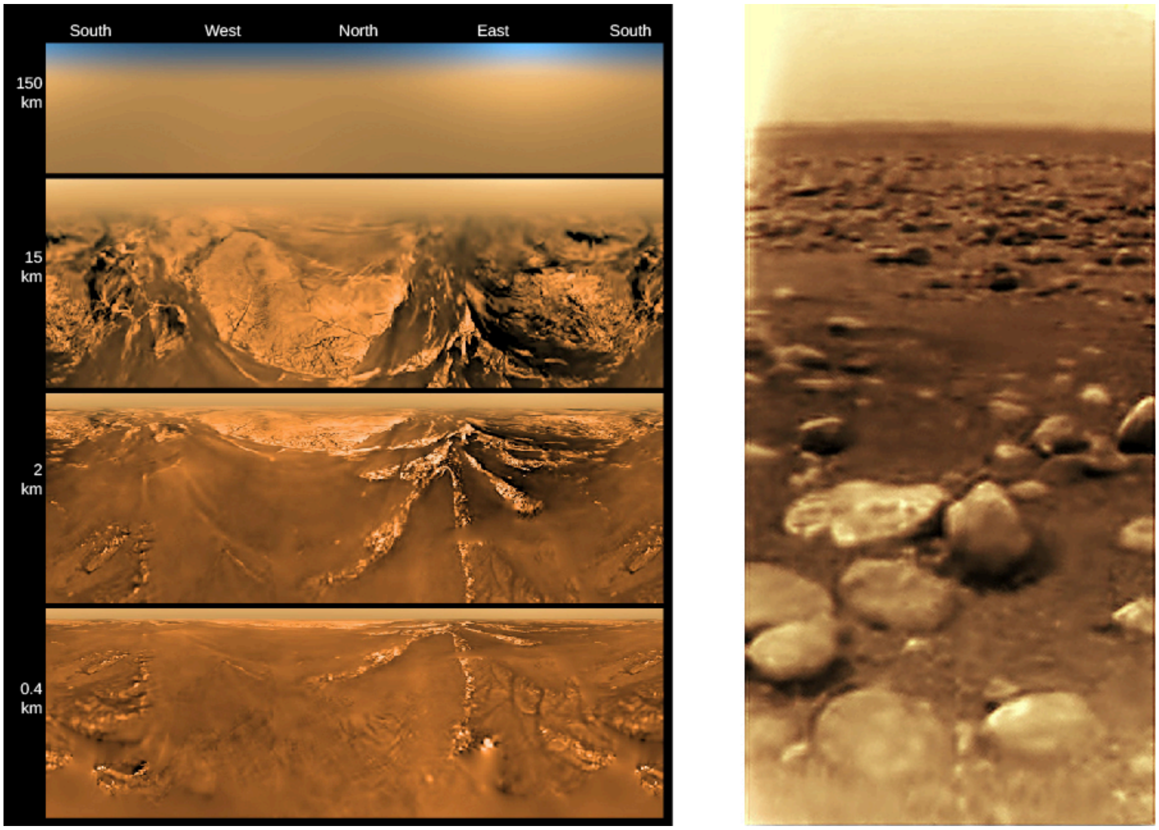


Figure 12.13 Views of the Surface of Titan. The left image shows the views of Titan from the descent camera, in a flattened projection, at different altitudes. The right image, taken after landing, shows a boulder-strewn surface illuminated by faint reddish sunlight. The boulders are composed of water 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.

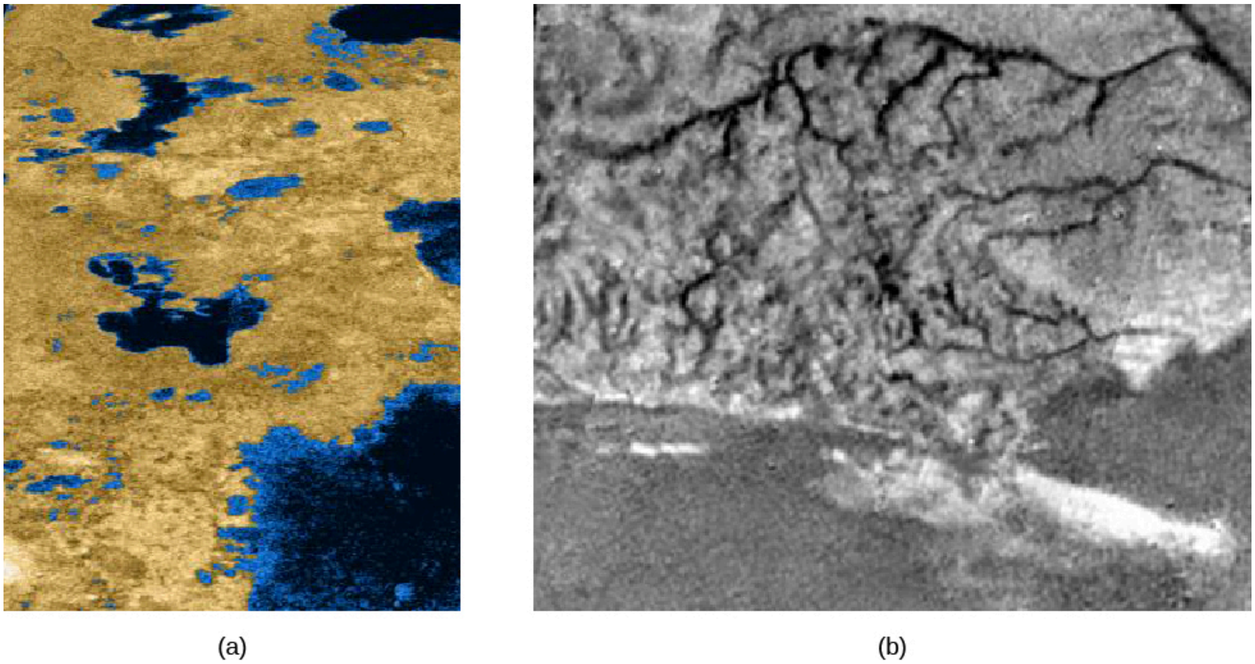


Figure 12.14 Titan's Lakes. (a) This Cassini image from a September 2006 flyby shows the liquid lakes on Titan. Their composition is most likely a combination of methane and ethane. (Since this is a radar image, the colors are artificially added. The dark blue areas are the smooth surfaces of the liquid 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.

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)** and the **flyover (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 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.

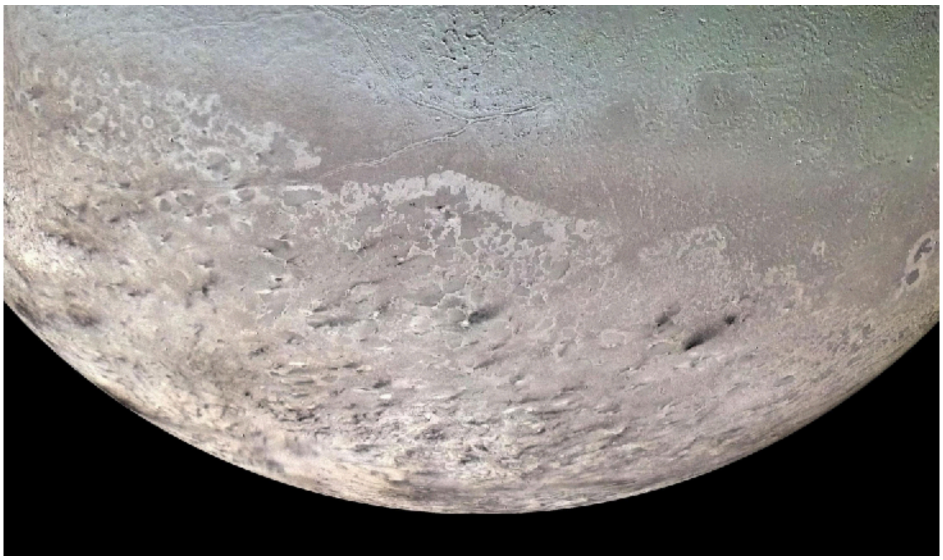


Figure 12.15 Neptune's Moon Triton. This mosaic of Voyager 2 images of Triton shows a wide range of surface features. The pinkish area at the bottom is Triton's large southern polar cap. The south pole of Triton faces the Sun here, and the slight heating effect is driving some of the material northward, 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.

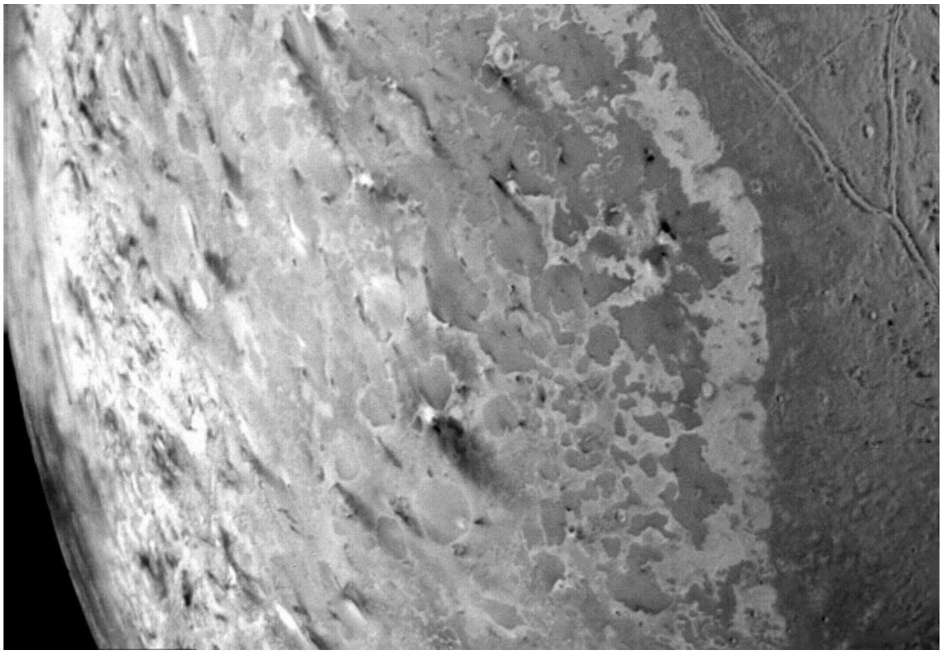


Figure 12.16 Triton's Geysers. This close-up view shows some of the geysers on Neptune's moon Triton, with the long trains of dust pointing to the lower right in this picture. (credit: modification of work by NASA/JPL)

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.

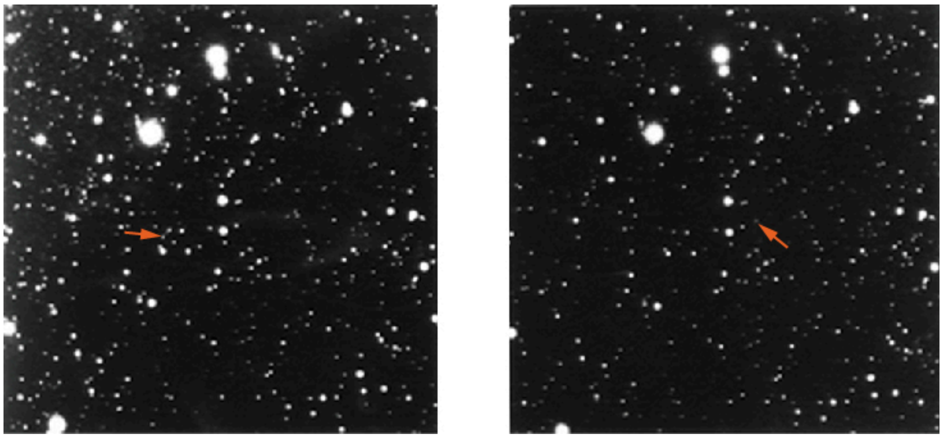


Figure 12.17 Pluto's Motion. Portions of the two photographs by which Clyde Tombaugh discovered Pluto in 1930. The left one was taken on January 23 and the right on January 29. Note that Pluto, indicated by an arrow, has moved among the stars during those six nights. If we hadn't put an arrow next to 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 small 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**).

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)** about Tombaugh's life as described by his children.

The Nature of Pluto

Using data from the New Horizons probe, astronomers have measured the diameter of Pluto as 2370 kilometers, only 60 perent as large as our Moon. From the diameter and mass, we find a density of 1.9 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**).

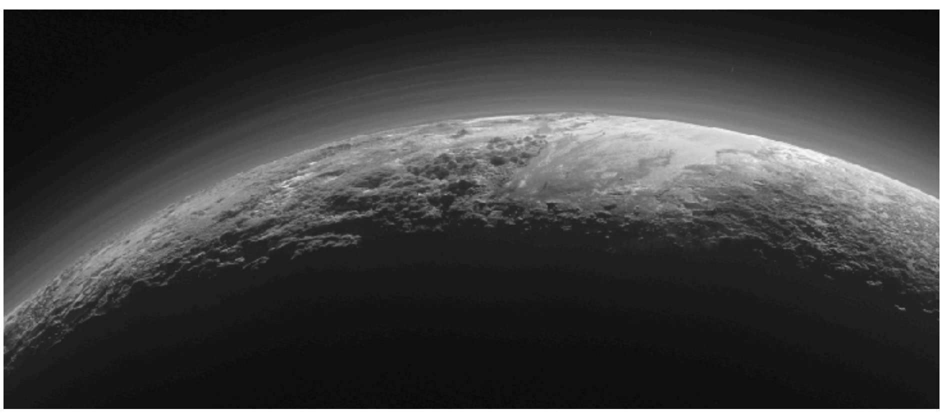


Figure 12.20 Haze Layers in the Atmosphere of Pluto. This is one of the highest-resolution photos of Pluto, taken by the New Horizons spacecraft 15 minutes after its closest approach. It shows 12 layers of haze. Note also the range of mountains with heights up to 3500 meters. (credit: modification of 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.

First Close-up Views 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 appear to be cratered, but adjacent to them is a nearly featureless light area in the lower right quadrant of this image. 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.

The light areas in the photo are lowland basins. These are apparently seas of frozen nitrogen, perhaps many kilometers deep. Both nitrogen and methane gas are able to escape from Pluto when it is in the part of its orbit close to the Sun, but only very slowly, so there is no reason that a vast bowl of frozen nitrogen could not persist for a long time.

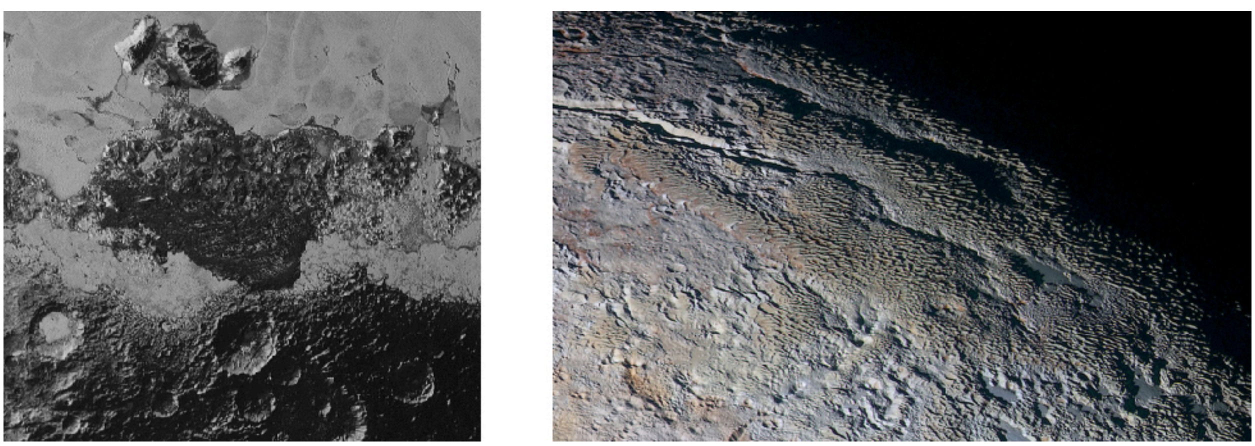
Figure 12.21 Global Color Image of Pluto. This New Horizons image clearly shows the variety of terrains on Pluto. The dark area in the lower left is covered with impact craters, while the large light area in the center and lower right is a flat basin devoid of craters. The colors you see are somewhat 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. At the right of this image we see the “shoreline” of the vast bowl of nitrogen ice we saw as the smooth region in Figure 12.21. Temporarily nicknamed the “Sputnik Plains,” after the first human object to get into space, this round region is roughly a thousand kilometers wide and shows intriguing cells or polygons that have an average width of more than 30 kilometers. The mountains in the middle are great blocks of frozen water ice, some reaching heights of 2 to 3 kilometers.

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 nicknamed 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. These are preliminary interpretations from just the first data coming back from New Horizons in 2015 and early 2016. As time goes on, scientists will have a better understanding of the unique geology of Pluto.



(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.

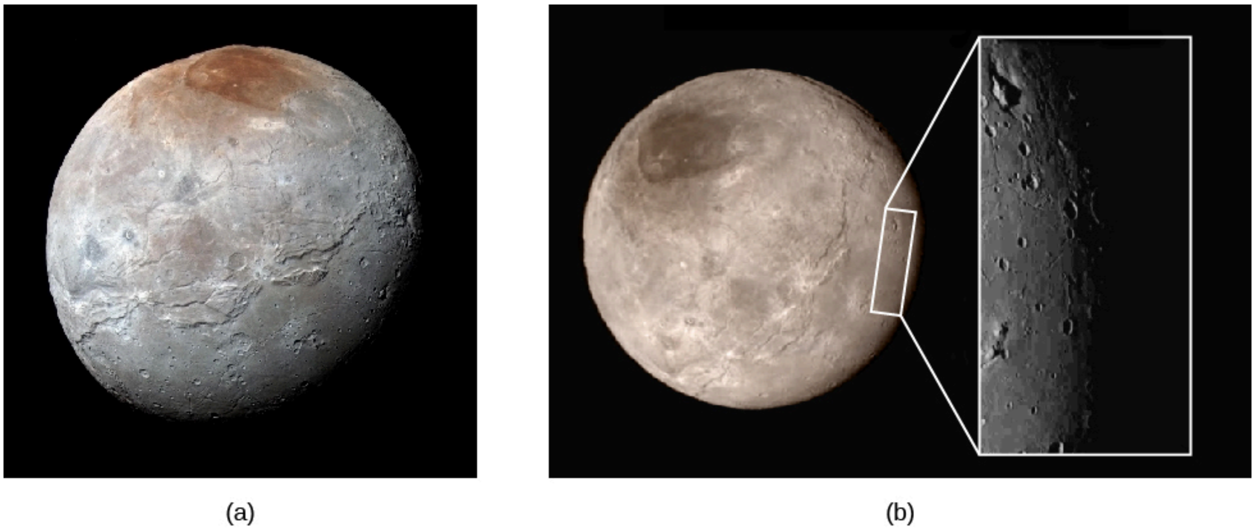


Figure 12.24 Pluto's Large Moon Charon. (a) In this New Horizons image, the color has been enhanced to bring out the color of the moon's strange red polar cap. Charon has a diameter of 1214 kilometers, and the resolution of this image is 3 kilometers. (b) Here we see the moon from a slightly different 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

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_{planet})	Mass (kg)	Reflectivity (%)
Jupiter	128,000	1.8	10^{10}(?)	?
Saturn	140,000	2.3	10^{19}	60
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.

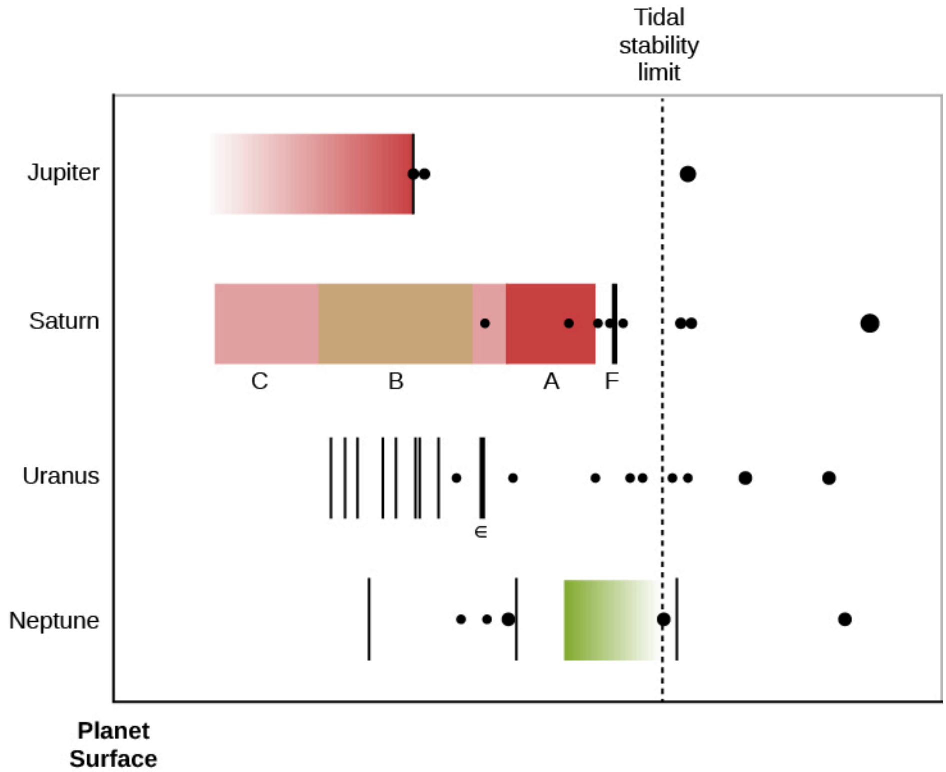


Figure 12.25 Four Ring Systems. This diagram shows the locations of the ring systems of the four giant planets. The left axis represents the planet's surface. The dotted vertical line is the limit inside which gravitational forces can break up moons (each planet's system is drawn to a different scale, 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_{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 have also given to the Cassini spacecraft exploring the Saturn system.

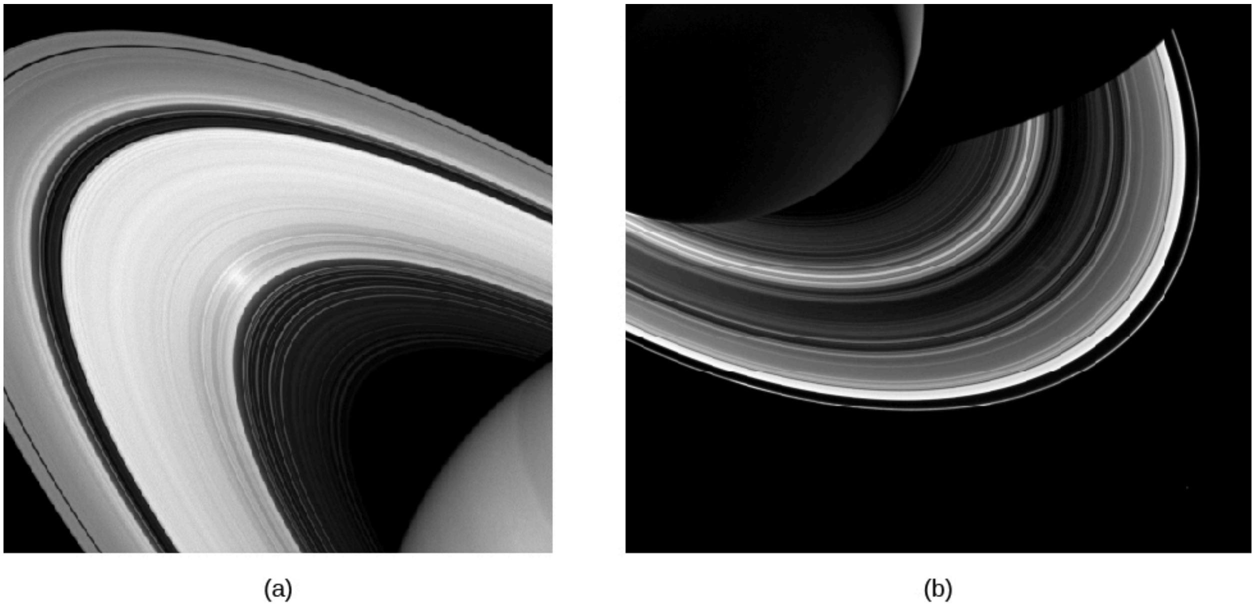


Figure 12.26 Saturn’s Rings as Seen from Above and Below. (a) The view from above is illuminated by direct sunlight. (b) The illumination seen from below is sunlight that has diffused through gaps in the rings. (credit a, b: modification of work by NASA/JPL-Caltech/Space Science Institute)

Selected Features in the Rings of Saturn

Ring Name[2]	Outer Edge (R_{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).

2 The ring letters are assigned in the order of their discovery.

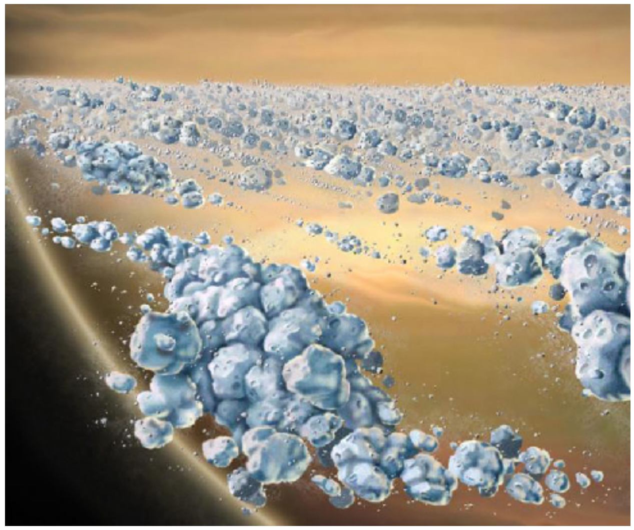
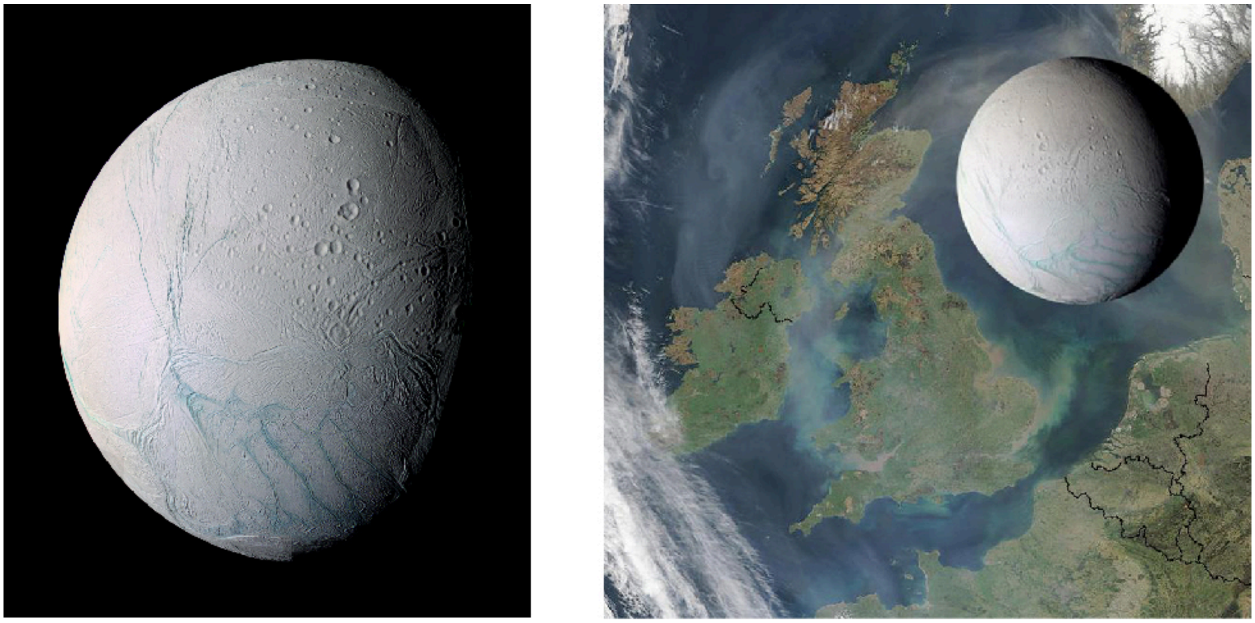


Figure 12.27 Artist's Idealized Impression of the Rings of Saturn as Seen from the Inside. Note that the rings are mostly made of pieces of water ice of different sizes. At the end of its mission, the Cassini spacecraft is planning to cut through one of the gaps in Saturn's rings, but it won't get this 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.



(a) (b)

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.

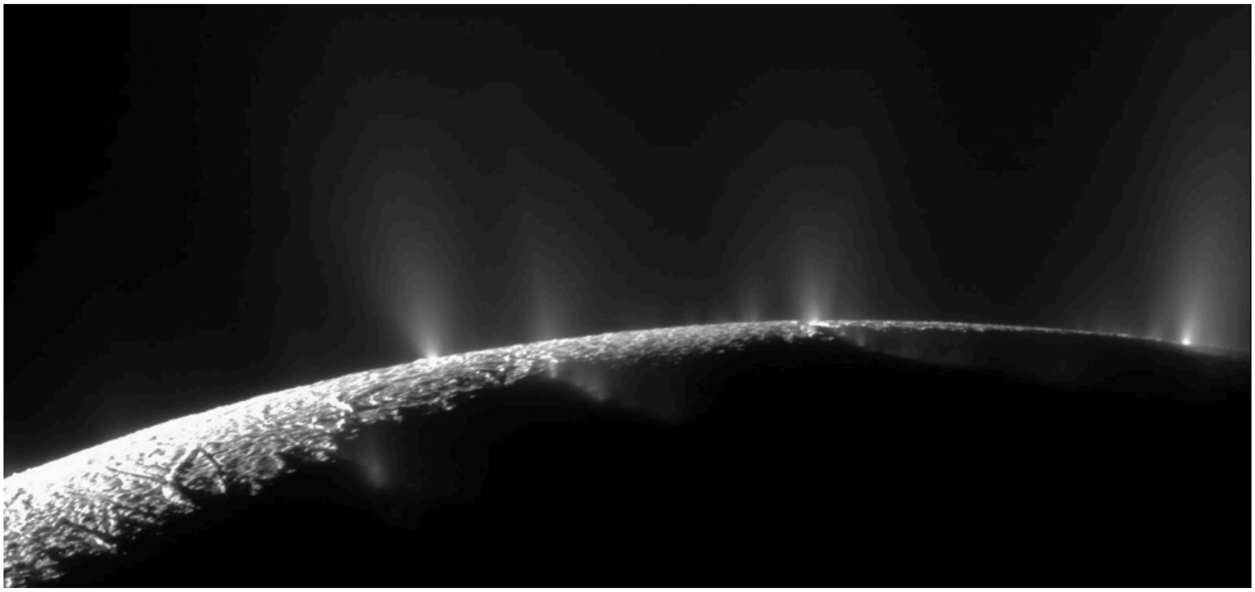


Figure 12.29 Geysers on Enceladus. This Cassini image shows a number of water geysers on Saturn's small moon Enceladus, apparently salty water from a subsurface source escaping through cracks in the surface. You can see curved lines of geysers along the four "tiger stripes" on the surface. (credit: modification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

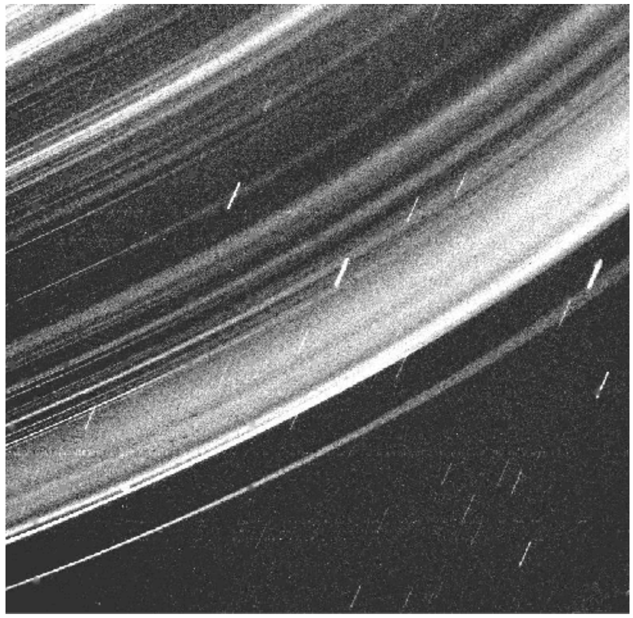


Figure 12.30 Rings of Uranus. The Voyager team had to expose this image for a long time to get a glimpse of Uranus' narrow dark rings. You can see the grainy structure of "noise" in the electronics of the camera in the picture background. (credit: modification of work by NASA/JPL)

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.

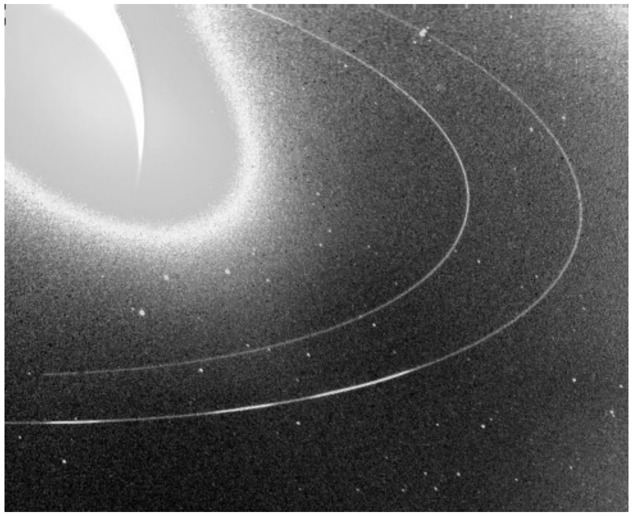


Figure 12.31 Rings of Neptune. This long exposure of Neptune's rings was photographed by Voyager 2. Note the two denser regions of the outer ring. (credit: modification of work by NASA/JPL)

LINK TO LEARNING

Mark Showalter (of the SETI Institute) and his colleagues maintain the **NASA's Planetary Ring Node (https://openstax.org/l/30NASArings)** 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)** 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 = 1.4×10^9 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.

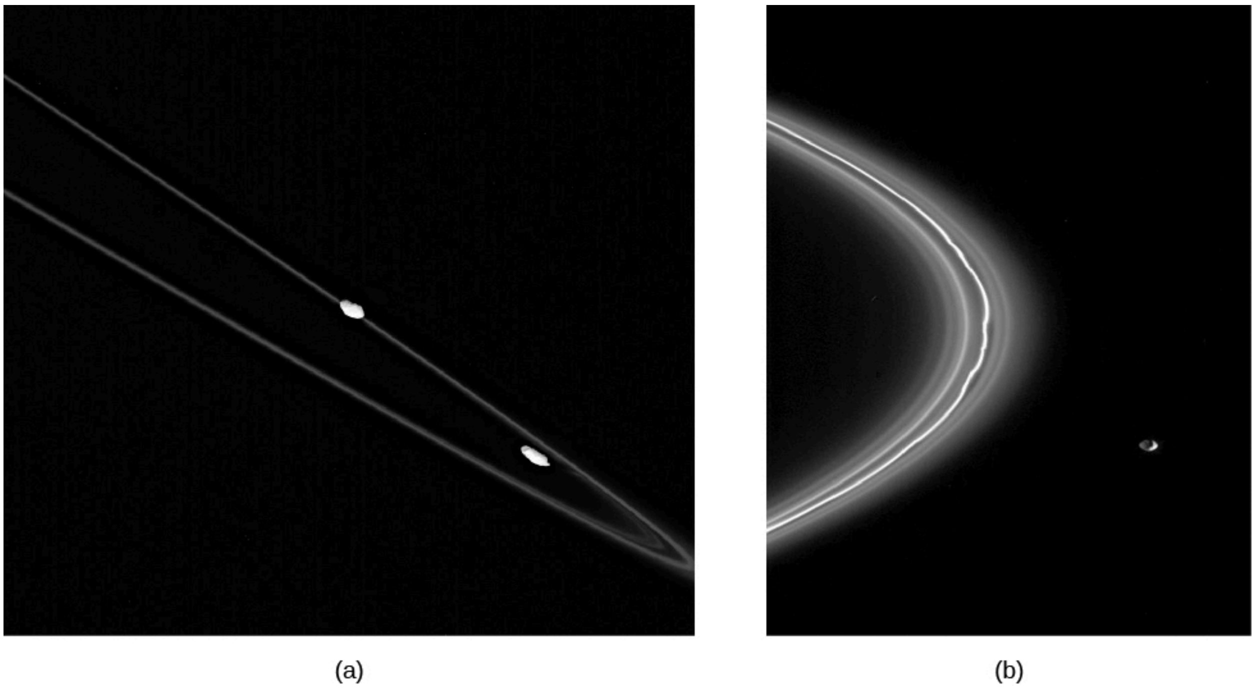


Figure 12.32 Saturn's F Ring and Its Shepherd Moons. (a) This Cassini image shows the narrow, complex F Ring of Saturn, with its two small shepherd moons Pandora (left) and Prometheus (right). (b) In this closer view, the shepherd moon Pandora (84 kilometers across) is seen next to the F ring, in which 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)** 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.

CHAPTER 12 REVIEW

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

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.

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

Pluto

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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.

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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)** Gives the latest news bulletins 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://itunes.apple.com/us/app/ju[iter-atlas/id352033947?mt=8 (https://itunes.apple.com/us/app/ju[iter-atlas/id352033947?mt=8)**
- Saturn Atlas: **https://itunes.apple.com/us/app/saturn-atlas/id352038051?mt=8 (https://itunes.apple.com/us/app/saturn-atlas/id352038051?mt=8)**

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)** . 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_lImiMg (http://www.youtube.com/watch?v=7pbj_lImiMg)** . 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=jIxQXGTI_mo (https://www.youtube.com/watch?v=jIxQXGTI_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://www.astrosociety.org/scifi. 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?

13

COMETS AND ASTEROIDS: DEBRIS OF THE SOLAR SYSTEM

Figure 13.1 Hale-Bopp. Comet Hale-Bopp was one of the most attractive and easily visible comets of the twentieth century. It is shown here as it appeared in the sky in March 1997. You can see the comet's long blue ion tail and the shorter white dust tail. You will learn about these two types of comet tails, and how they form, in this chapter. (credit: modification of work by ESO/E. Slawik)

Chapter Outline

Thinking Ahead

Hundreds of smaller members of the solar system—asteroids and comets—are known to have crossed Earth's orbit in the past, and many others will do so in centuries ahead. What could we do if we knew a few years in advance that one of these bodies would hit Earth?

To understand the early history of life on Earth, scientists study ancient fossils. To reconstruct the early history of the solar system, we need cosmic fossils—materials that formed when our system was very young. However, reconstructing the early history of the solar system by looking just at the planets is almost as difficult as determining the circumstances of human birth by merely looking at an adult.

Instead, we turn to the surviving remnants of the creation process—ancient but smaller objects in our cosmic neighborhood. Asteroids are rocky or metallic and contain little *volatile* (easily evaporated) material. Comets are small icy objects that contain frozen water and other volatile materials but with solid grains mixed in. In the deep freeze beyond Neptune, we also have a large reservoir of material unchanged since the formation of the solar system, as well as a number of dwarf planets.

13.1 ASTEROIDS

Learning Objectives

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

- Outline the story of the discovery of asteroids and describe their typical orbits
- Describe the composition and classification of the various types of asteroids
- Discuss what was learned from spacecraft missions to several asteroids

The asteroids are mostly found in the broad space between Mars and Jupiter, a region of the solar system called the *asteroid belt*. Asteroids are too small to be seen without a telescope; the first of them was not discovered until the beginning of the nineteenth century.

Discovery and Orbits of the Asteroids

In the late 1700s, many astronomers were hunting for an additional planet they thought should exist in the gap between the orbits of Mars and Jupiter. The Sicilian astronomer Giovanni Piazzi thought he had found this missing planet in 1801, when he discovered the first asteroid (or as it was later called, “minor planet”) orbiting at 2.8 AU from the Sun. His discovery, which he named Ceres, was quickly followed by the detection of three other little planets in similar orbits.

Clearly, there was not a single missing planet between Mars and Jupiter but rather a whole group of objects, each much smaller than our Moon. (An analogous discovery history has played out in slow motion in the outer solar system. Pluto was discovered beyond Neptune in 1930 and was initially called a planet, but early in the twenty-first century, several other similar objects were found. We now call all of them dwarf planets.)

By 1890, more than 300 of these minor planets or **asteroids** had been discovered by sharp-eyed observers. In that year, Max Wolf at Heidelberg introduced astronomical photography to the search for asteroids, greatly accelerating the discovery of these dim objects. In the twenty-first century, searchers use computer-driven electronic cameras, another leap in technology. More than half a million asteroids now have well-determined orbits.

Asteroids are given a number (corresponding to the order of discovery) and sometimes also a name. Originally, the names of asteroids were chosen from goddesses in Greek and Roman mythology. After exhausting these and other female names (including, later, those of spouses, friends, flowers, cities, and others), astronomers turned to the names of colleagues (and other people of distinction) whom they wished to honor. For example, asteroids 2410, 4859, and 68448 are named Morrison, Fraknoi, and Sidneywolff, for the three original authors of this textbook.

The largest asteroid is Ceres (numbered 1), with a diameter just less than 1000 kilometers. As we saw, Ceres was considered a planet when it was discovered but later was called an asteroid (the first of many.) Now, it has again been reclassified and is considered one of the dwarf planets, like Pluto (see the chapter on **Moons, Rings and Pluto**). We still find it convenient, however, to discuss Ceres as the largest of the asteroids. Two other asteroids, Pallas and Vesta, have diameters of about 500 kilometers, and about 15 more are larger than 250 kilometers (see **Table 13.1**). The number of asteroids increases rapidly with decreasing size; there are about 100 times more objects 10 kilometers across than there are 100 kilometers across. By 2016, nearly a million asteroids have been discovered by astronomers.

LINK TO LEARNING

The **Minor Planet Center (https://openstaxcollege.org/l/30minplancen)** is a worldwide repository of data on asteroids. Visit it online to find out about the latest discoveries related to the small bodies in our solar system. (Note that some of the material on this site is technical; it's best to click on the menu tab for the "public" for information more at the level of this textbook.)

The Largest Asteroids

#	Name	Year of Discovery	Orbit's Semimajor Axis (AU)	Diameter (km)	Compositional Class
1	Ceres	1801	2.77	940	C (carbonaceous)
2	Pallas	1802	2.77	540	C (carbonaceous)
3	Juno	1804	2.67	265	S (stony)
4	Vesta	1807	2.36	510	basaltic
10	Hygiea	1849	3.14	410	C (carbonaceous)
16	Psyche	1852	2.92	265	M (metallic)
31	Euphrosyne	1854	3.15	250	C (carbonaceous)
52	Europa	1858	3.10	280	C (carbonaceous)
65	Cybele	1861	3.43	280	C (carbonaceous)
87	Sylvia	1866	3.48	275	C (carbonaceous)
451	Patientia	1899	3.06	260	C (carbonaceous)
511	Davida	1903	3.16	310	C (carbonaceous)
704	Interamnia	1910	3.06	310	C (carbonaceous)

Table 13.1

The asteroids all revolve about the Sun in the same direction as the planets, and most of their orbits lie near the plane in which Earth and other planets circle. The majority of asteroids are in the **asteroid belt**, the region between Mars and Jupiter that contains all asteroids with orbital periods between 3.3 to 6 years (Figure 13.2). Although more than 75% of the known asteroids are in the belt, they are not closely spaced (as they are sometimes depicted in science fiction movies). The volume of the belt is actually very large, and the typical spacing between objects (down to 1 kilometer in size) is several million kilometers. (This was fortunate for spacecraft like Galileo, Cassini, *Rosetta*, and New Horizons, which needed to travel through the asteroid belt without a collision.)

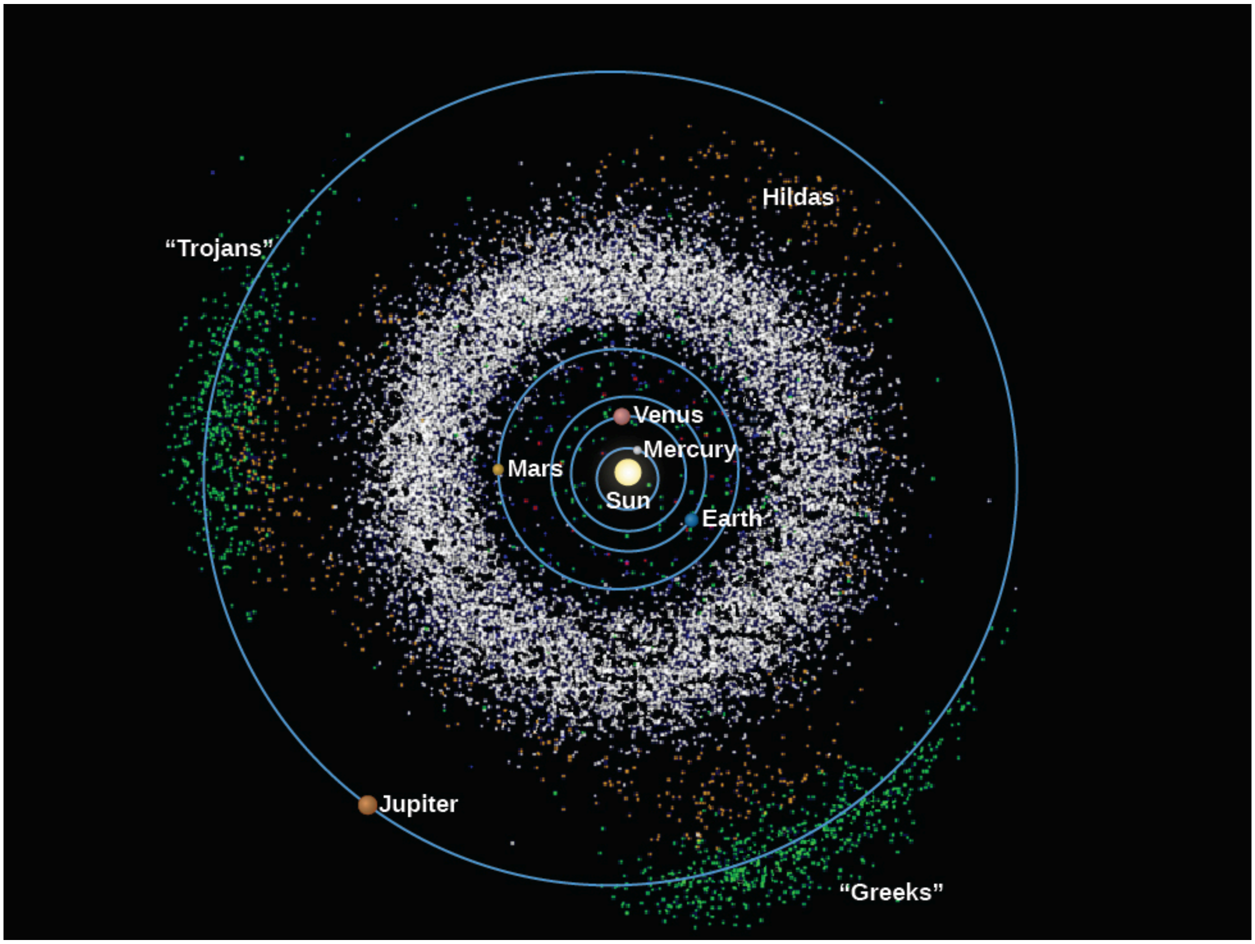


Figure 13.2 Asteroids in the Solar System. This computer-generated diagram shows the positions of the asteroids known in 2006. If the asteroid sizes were drawn to scale, none of the dots representing an asteroid would be visible. Here, the asteroid dots are too big and give a false impression of how crowded the asteroid belt would look if you were in it. Note that in addition to those in the asteroid belt, there are also asteroids in the inner solar system and some along Jupiter's orbit (such as the Trojans and Greeks groups), controlled by the giant planet's gravity.

Still, over the long history of our solar system, there have been a good number of collisions among the asteroids themselves. In 1918, the Japanese astronomer Kiyotsugu Hirayama found that some asteroids fall into *families*, groups with similar orbital characteristics. He hypothesized that each family may have resulted from the breakup of a larger body or, more likely, from the collision of two asteroids. Slight differences in the speeds with which the various fragments left the collision scene account for the small spread in orbits now observed for the different asteroids in a given family. Several dozen such families exist, and observations have shown that individual members of most families have similar compositions, as we would expect if they were fragments of a common parent.

LINK TO LEARNING

You can see a **dramatic animated video (https://openstaxcollege.org/l/30anividastorb)** showing the orbits of 100,000 asteroids found by one sky survey. As the 3-minute video goes on, you get to see the orbits of the planets and how the asteroids are distributed in the solar system. But note that all such videos are misleading in one sense. The asteroids themselves are really small compared to the distances covered, so they have to be depicted as larger points to be visible. If you were in the asteroid belt, there would be far more empty space than asteroids.

Composition and Classification

Asteroids are as different as black and white. The majority are very dark, with reflectivity of only 3 to 4%, like a lump of coal. However, another large group has a typical reflectivity of 15%. To understand more about these differences and how they are related to chemical composition, astronomers study the spectrum of the light reflected from asteroids for clues about their composition.

The dark asteroids are revealed from spectral studies to be *primitive* bodies (those that have changed little chemically since the beginning of the solar system) composed of silicates mixed with dark, organic carbon compounds. These are known as C-type asteroids (“C” for carbonaceous). Two of the largest asteroids, Ceres and Pallas, are primitive, as are almost all of the asteroids in the outer part of the belt.

The second most populous group is the S-type asteroids, where “S” stands for a stony or silicate composition. Here, the dark carbon compounds are missing, resulting in higher reflectivity and clearer spectral signatures of silicate minerals. The S-type asteroids are also chemically primitive, but their different composition indicates that they were probably formed in a different location in the solar system from the C-type asteroids.

Asteroids of a third class, much less numerous than those of the first two, are composed primarily of metal and are called M-type asteroids (“M” for metallic). Spectroscopically, the identification of metal is difficult, but for at least the largest M-type asteroid, Psyche, this identification has been confirmed by radar. Since a metal asteroid, like an airplane or ship, is a much better reflector of radar than is a stony object, Psyche appears bright when we aim a radar beam at it.

How did such metal asteroids come to be? We suspect that each came from a parent body large enough for its molten interior to settle out or differentiate, and the heavier metals sank to the center. When this parent body shattered in a later collision, the fragments from the core were rich in metals. There is enough metal in even a 1-kilometer M-type asteroid to supply the world with iron and many other industrial metals for the foreseeable future, if we could bring one safely to Earth.

In addition to the M-type asteroids, a few other asteroids show signs of early heating and differentiation. These have basaltic surfaces like the volcanic plains of the Moon and Mars; the large asteroid Vesta (discussed in a moment) is in this last category.

The different classes of asteroids are found at different distances from the Sun (**Figure 13.3**). By tracing how asteroid compositions vary with distance from the Sun, we can reconstruct some of the properties of the solar nebula from which they originally formed.

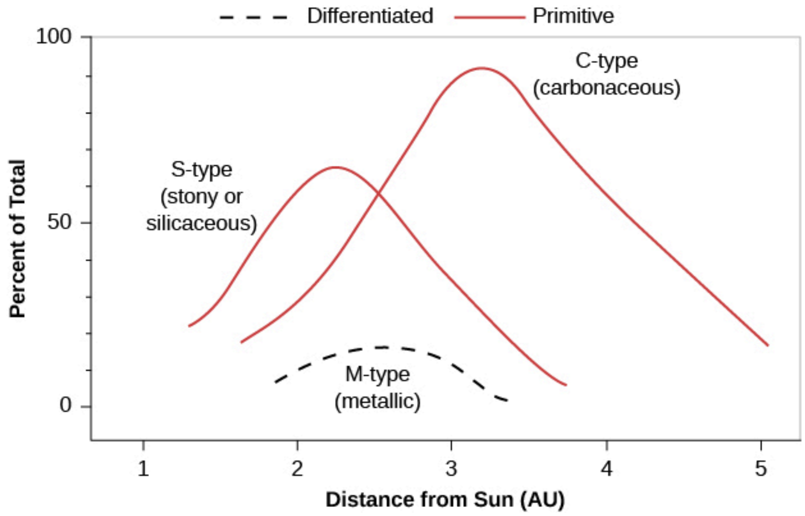


Figure 13.3 Where Different Types of Asteroids Are Found. Asteroids of different composition are distributed at different distances from the Sun. The S-type and C-type are both primitive; the M-type consists of cores of differentiated parent bodies.

Vesta: A Differentiated Asteroid

Vesta is one of the most interesting of the asteroids. It orbits the Sun with a semi-major axis of 2.4 AU in the inner part of the asteroid belt. Its relatively high reflectivity of almost 30% makes it the brightest asteroid, so bright that it is actually visible to the unaided eye if you know just where to look. But its real claim to fame is that its surface is covered with basalt, indicating that Vesta is a differentiated object that must once have been volcanically active, in spite of its small size (about 500 kilometers in diameter).

Meteorites from Vesta's surface (**Figure 13.4**), identified by comparing their spectra with that of Vesta itself, have landed on Earth and are available for direct study in the laboratory. We thus know a great deal about this asteroid. The age of the lava flows from which these meteorites derived has been measured at 4.4 to 4.5 billion years, very soon after the formation of the solar system. This age is consistent with what we might expect for volcanoes on Vesta; whatever process heated such a small object was probably intense and short-lived. In 2016, a meteorite fell in Turkey that could be identified with a particular lava flow as revealed by the orbiting *Dawn* spacecraft.

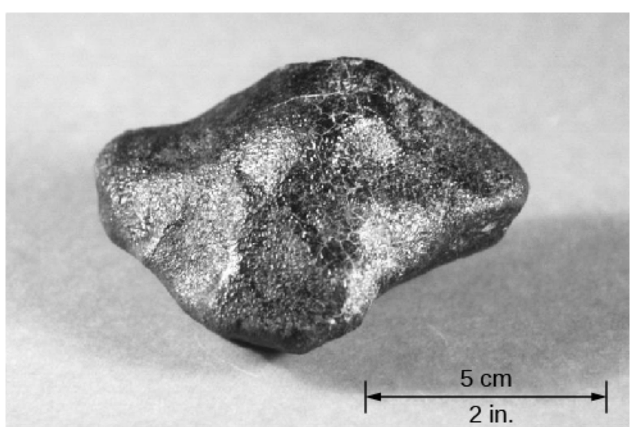


Figure 13.4 Piece of Vesta. This meteorite (rock that fell from space) has been identified as a volcanic fragment from the crust of asteroid Vesta. (credit: modification of work by R. Kempton (New England Meteoritical Services))

Asteroids Up Close

On the way to its 1995 encounter with Jupiter, the Galileo spacecraft was targeted to fly close to two main-belt S-type asteroids called Gaspra and Ida. The Galileo camera revealed both as long and highly irregular (resembling a battered potato), as befits fragments from a catastrophic collision (**Figure 13.5**).

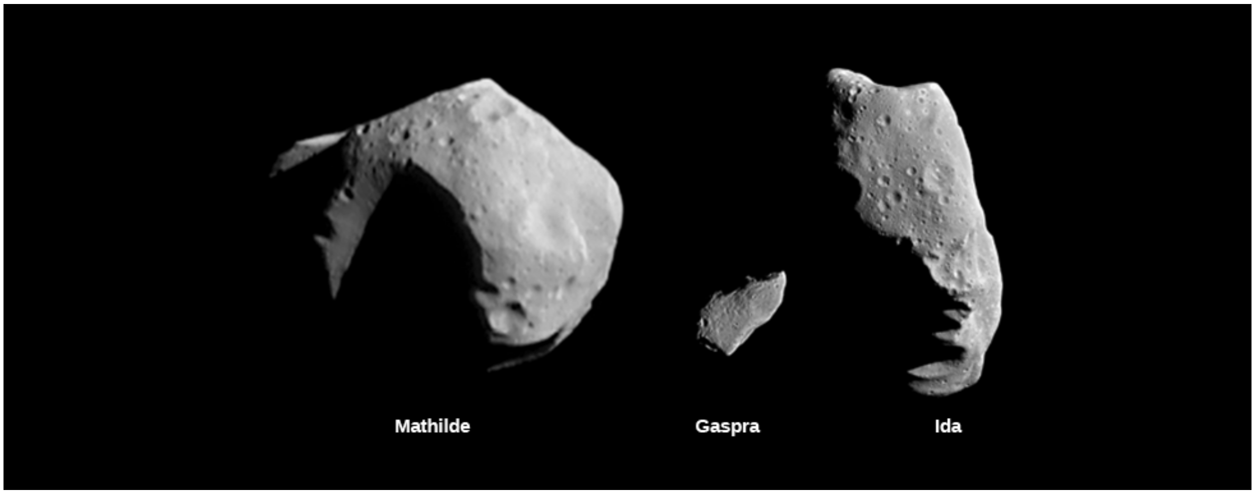


Figure 13.5 Mathilde, Gaspra, and Ida. The first three asteroids photographed from spacecraft flybys, printed to the same scale. Gaspra and Ida are S-type and were investigated by the Galileo spacecraft; Mathilde is C-type and was a flyby target for the NEAR-Shoemaker spacecraft. (credit: modification of work by NEAR Project, Galileo Project, NASA)

The detailed images allowed us to count the craters on Gaspra and Ida, and to estimate the length of time their surfaces have been exposed to collisions. The Galileo scientists concluded that these asteroids are only about 200 million years old (that is, the collisions that formed them took place about 200 million years ago). Calculations suggest that an asteroid the size of Gaspra or Ida can expect another catastrophic collision sometime in the next billion years, at which time it will be disrupted to form another generation of still-smaller fragments.

The greatest surprise of the Galileo flyby of Ida was the discovery of a moon (which was then named Dactyl), in orbit about the asteroid (**Figure 13.6**). Although only 1.5 kilometers in diameter, smaller than many college campuses, Dactyl provides scientists with something otherwise beyond their reach—a measurement of the mass and density of Ida using Kepler's laws. The moon's distance of about 100 kilometers and its orbital period of about 24 hours indicate that Ida has a density of approximately 2.5 g/cm^3, which matches the density of primitive rocks. Subsequently, both large visible-light telescopes and high-powered planetary radar have discovered many other asteroid moons, so that we are now able to accumulate valuable data on asteroid masses and densities.

Figure 13.6 Ida and Dactyl. The asteroid Ida and its tiny moon Dactyl (the small body off to its right), were photographed by the Galileo spacecraft in 1993. Irregularly shaped Ida is 56 kilometers in its longest dimension, while Dactyl is about 1.5 kilometers across. The colors have been intensified in this image; to the eye, all asteroids look basically gray. (credit: modification of work by NASA/JPL)

By the way, Phobos and Deimos, the two small moons of Mars, are probably captured asteroids (**Figure 13.7**). They were first studied at close range by the Viking orbiters in 1977 and later by *Mars Global Surveyor*. Both are irregular, somewhat elongated, and heavily created, resembling other smaller asteroids. Their largest dimensions are about 26 kilometers and 16 kilometers, respectively. The small outer moons of Jupiter and Saturn were probably also captured from passing asteroids, perhaps early in the history of the solar system.

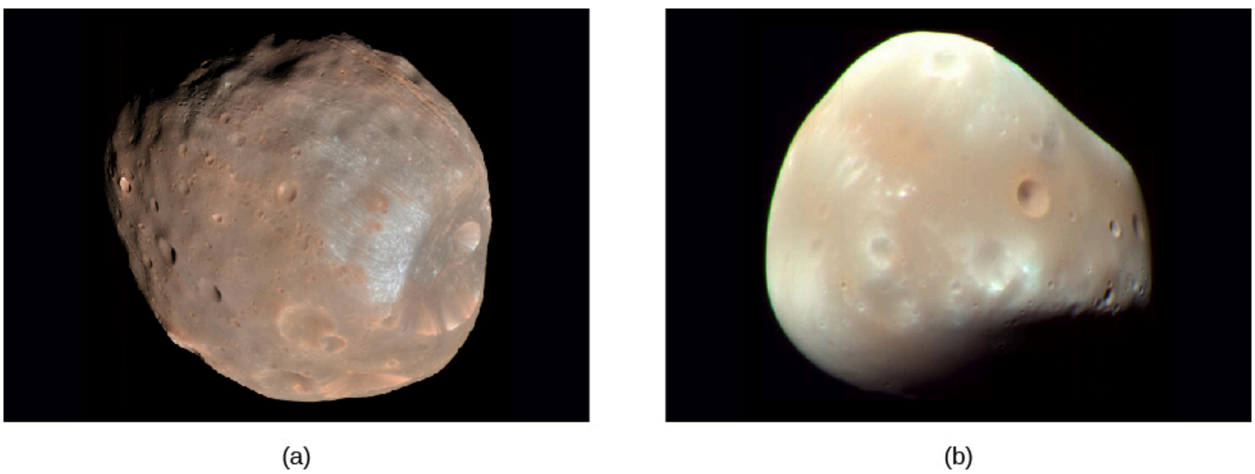


Figure 13.7 Moons of Mars. The two small moons of Mars, (a) Phobos and (b) Deimos, were discovered in 1877 by American astronomer Asaph Hall. Their surface materials are similar to many of the asteroids in the outer asteroid belt, leading astronomers to believe that the two moons may be captured asteroids. (credit a: modification of work by NASA; credit b: modification of work by NASA/JPL-Caltech/University of Arizona)

Beginning in the 1990s, spacecraft have provided close looks at several more asteroids. The Near Earth Asteroid Rendezvous (NEAR) spacecraft went into orbit around the S-type asteroid Eros, becoming a temporary moon of this asteroid. On its way to Eros, the *NEAR* spacecraft was renamed after planetary geologist Eugene Shoemaker, a pioneer in our understanding of craters and impacts.

For a year, the NEAR-Shoemaker spacecraft orbited the little asteroid at various altitudes, measuring its surface and interior composition as well as mapping Eros from all sides (**Figure 13.8**). The data showed that Eros is made of some of the most chemically primitive materials in the solar system. Several other asteroids have been revealed as made of loosely bound rubble throughout, but not Eros. Its uniform density (about the same as that of Earth's crust) and extensive global-scale grooves and ridges show that it is a cracked but solid rock.

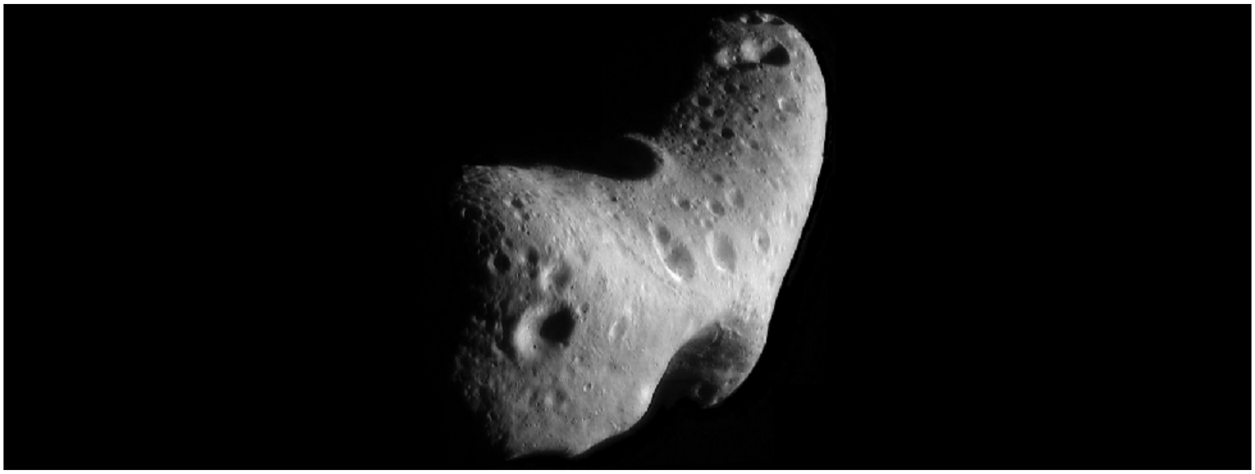


Figure 13.8 Looking Down on the North Pole of Eros. This view was constructed from six images of the asteroid taken from an altitude of 200 kilometers. The large crater at the top has been named Psyche (after the maiden who was Eros' lover in classical mythology) and is about 5.3 kilometers wide. A saddle-shaped region can be seen directly below it. Craters of many different sizes are visible. (credit: modification of work by NASA/JHUPL)

Eros has a good deal of loose surface material that appears to have slid down toward lower elevations. In some places, the surface rubble layer is 100 meters deep. The top of loose soil is dotted with scattered, half-buried boulders. There are so many of these boulders that they are more numerous than the craters. Of course, with the gravity so low on this small world, a visiting astronaut would find loose boulders rolling toward her pretty slowly and could easily leap high enough to avoid being hit by one. Although the NEAR-Shoemaker spacecraft was not constructed as a lander, at the end of its orbital mission in 2000, it was allowed to fall gently to the surface, where it continued its chemical analysis for another week.

In 2003, Japan's Hayabusa 1 mission not only visited a small asteroid but also brought back samples to study in laboratories on Earth. The target S-type asteroid, Itokawa (shown in **Figure 13.9**), is much smaller than Eros, only about 500 meters long. This asteroid is elongated and appears to be the result of the collision of two separate asteroids long ago. There are almost no impact craters, but an abundance of boulders (like a pile of rubble) on the surface.

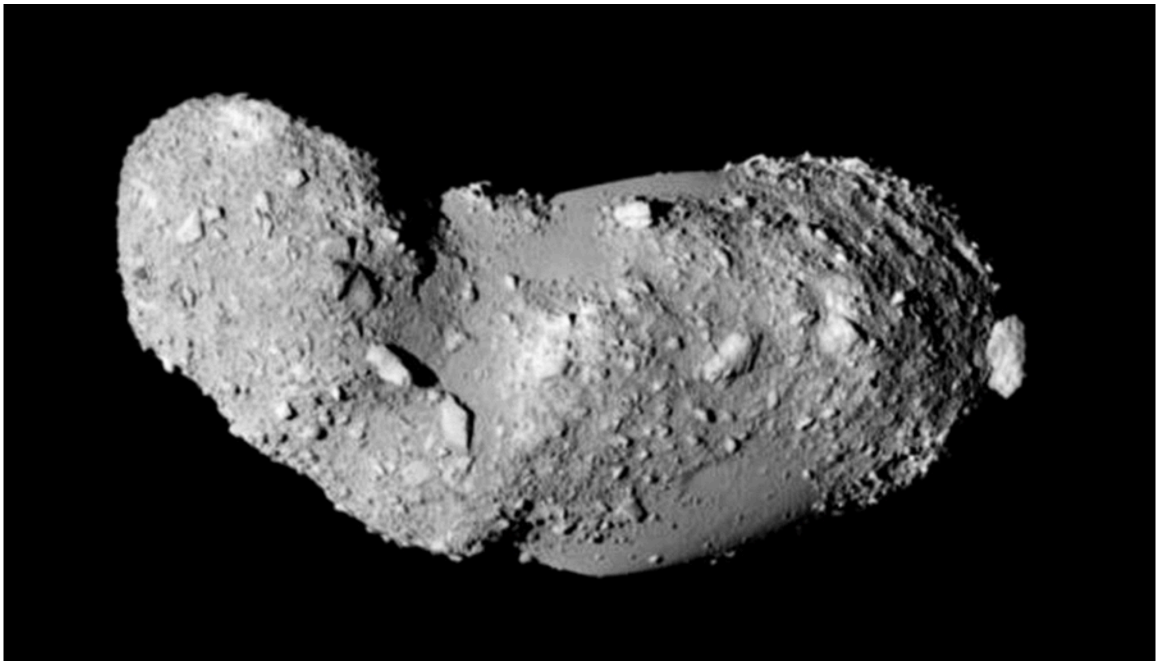
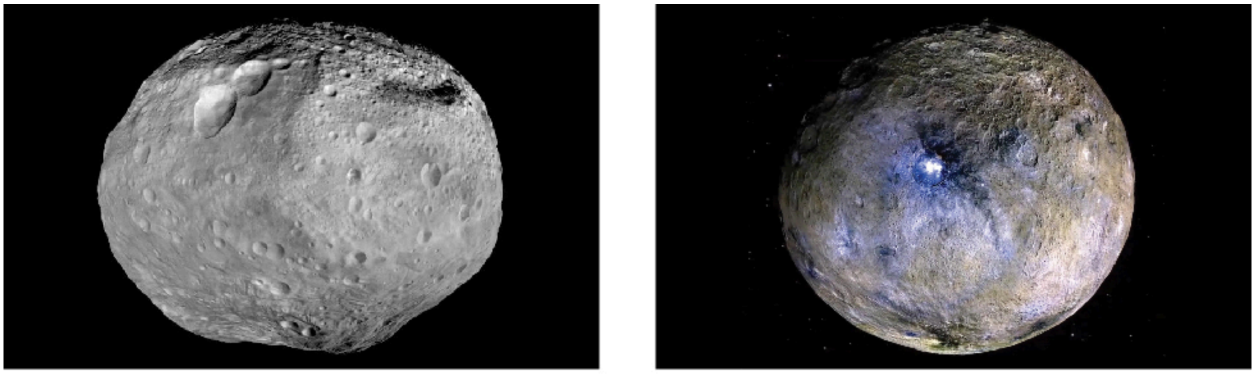


Figure 13.9 Asteroid Itokawa. The surface of asteroid Itokawa appears to have no craters. Astronomers have hypothesized that its surface consists of rocks and ice chunks held together by a small amount of gravity, and its interior is probably also a similar rubble pile. (credit: JAXA)

The *Hayabusa* spacecraft was designed not to land, but to touch the surface just long enough to collect a small sample. This tricky maneuver failed on its first try, with the spacecraft briefly toppling over on its side. Eventually, the controllers were successful in picking up a few grains of surface material and transferring them into the return capsule. The 2010 reentry into Earth's atmosphere over Australia was spectacular (**Figure 13.10**), with a fiery breakup of the spacecraft, while a small return capsule successfully parachuted to the surface. Months of careful extraction and study of more than a thousand tiny dust particles confirmed that the surface of Itokawa had a composition similar to a well-known class of primitive meteorites. We estimate that the dust grains *Hayabusa* picked up had been exposed on the surface of the asteroid for about 8 million years.

Figure 13.10 Hayabusa Return. This dramatic image shows the *Hayabusa* probe breaking up upon reentry. The return capsule, which separated from the main spacecraft and parachuted to the surface, glows at the bottom right. (credit: modification of work by NASA Ames/Jesse Carpenter/Greg Merkes)

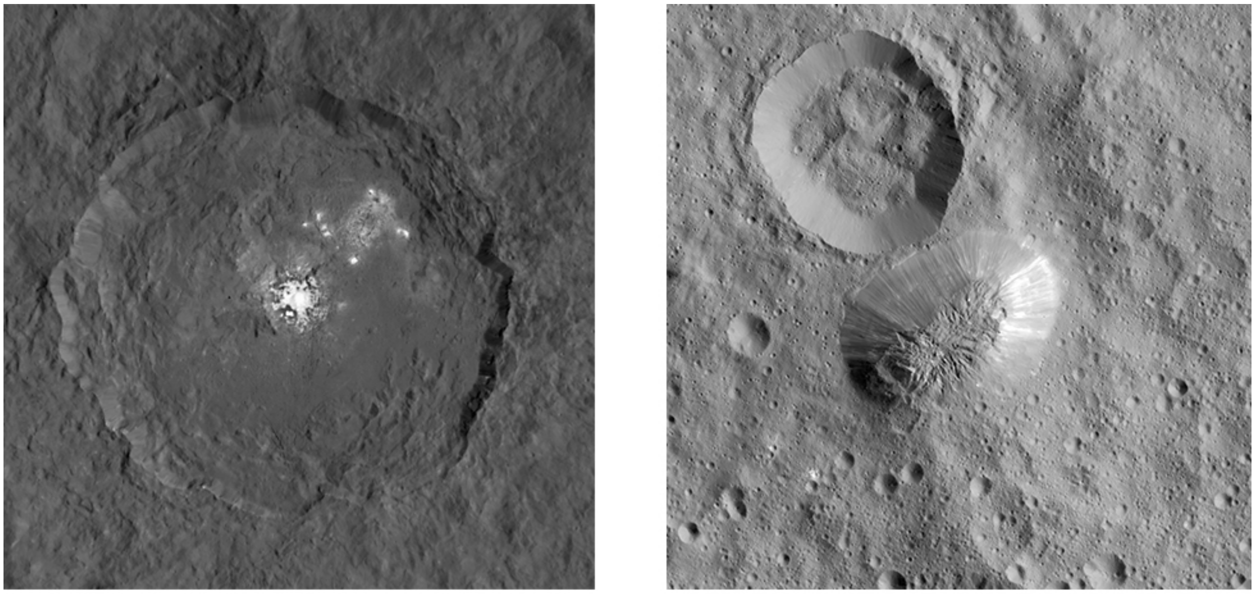
The most ambitious asteroid space mission (called Dawn) has visited the two largest main belt asteroids, Ceres and Vesta, orbiting each for about a year (**Figure 13.11**). Their large sizes (diameters of about 1000 and 500 kilometers, respectively) make them appropriate for comparison with the planets and large moons. Both turned out to be heavily cratered, implying their surfaces are old. On Vesta, we have now actually located the large impact craters that ejected the basaltic meteorites previously identified as coming from this asteroid. These craters are so large that they sample several layers of Vesta’s crustal material.



(a) (b)

Figure 13.11 Vesta and Ceres. The NASA *Dawn* spacecraft took these images of the large asteroids (a) Vesta and (b) Ceres. (a) Note that Vesta is not round, as Ceres (which is considered a dwarf planet) is. A mountain twice the height of Mt. Everest on Earth is visible at the very bottom of the Vesta image. (b) The image of Ceres has its colors exaggerated to bring out differences in composition. You can see a white feature in Occator crater near the center of the image. (credit a, b: modification of work by NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

Ceres has not had a comparable history of giant impacts, so its surface is covered with craters that look more like those from the lunar highlands. One big surprise at Ceres is the presence of very bright white spots, associated primarily with the central peaks of large craters (**Figure 13.12**). The light-colored mineral is primarily salt, released from the interior. After repeated close flybys, data from the NASA Dawn spacecraft indicated that Ceres has (or has had) a subsurface ocean of water, with occasional eruptions on the surface. The most dramatic is the 4 kilometer tall ice volcano called Ahuna Mons (see **Figure 13.12**).



(a) (b)

Figure 13.12 White Spots in a Larger Crater on Ceres. White Spots in a Larger Crater on Ceres. (a) These bright features appear to be salt deposits in a Ceres crater called Occator, which is 92 kilometers across. (b) Ahuna Mons is an isolated mountain on Ceres, 4 kilometers high. It is thought to be an intrusion of ice from the interior. (credit a: modification of work by NASA/JPL-Caltech/UCLA/MPS/DLR/IDA; credit b: modification of work by NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI)

In late 2017, something entirely new was discovered: an interstellar asteroid. This visitor was found at a distance of 33 million kilometers with a survey telescope on Haleakala, Hawaii. As astronomers followed up on the discovery, it quickly became apparent that this asteroid was travelling far too fast to be part of the Sun’s family. Its orbit is a hyperbola, and when discovered it was already rapidly leaving the inner solar system. Although it was too distant for imaging by even large telescopes, its size and shape could be estimated from its brightness and rapid light fluctuations. It is highly elongated, with an approximately cylindrical shape. The nominal dimensions are about 200 meters in length and only 35 meters across, the most extreme of any natural object. Large objects, like planets and moons, are pulled by their own gravity into roughly spherical shapes, and even small asteroids and comets (often described as “potato-shaped”) rarely have irregularities of more than a factor of two.

This asteroid was named ‘Oumuamua, a Hawaiian word meaning “scout” or “first to reach out.” In a way, the discovery of an interstellar asteroid or comet was not unexpected. Early in solar system history, before the planet orbits sorted themselves into stable, non-intersecting paths all in the same plane, we estimate that quite a lot of mass was ejected, either whole planets or more numerous smaller fragments. Even today, an occasional comet coming in from the outer edges of the solar system can have its orbit changed by gravitational interaction with Jupiter and the Sun, and some of these escape on hyperbolic trajectories. As we have recently learned that planetary systems are common, the question became: where are similar debris objects ejected from other planetary systems? Now we have found one, and improved surveys will soon add others to this category.

LINK TO LEARNING

View an artist’s rendering of the asteroid ‘Oumuamua **(https://www.openstax.org/l/30/oumuamua)**

(https://www.openstax.org/l/30/oumuamua) by the ESO. Although it was not close enough to Earth to be imaged, its long slender shape was indicated by its rapid variation in brightness as it rotated.

LINK TO LEARNING

The space agencies involved with the Dawn mission have produced nice animated “flyover” videos of **Vesta (https://openstaxcollege.org/l/30vestaflyover)** and **Ceres (https://openstaxcollege.org/l/30ceresflyover)** available online.

13.2 ASTEROIDS AND PLANETARY DEFENSE

Learning Objectives

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

- Recognize the threat that near-Earth objects represent for Earth
- Discuss possible defensive strategies to protect our planet

Not all asteroids are in the main asteroid belt. In this section, we consider some special groups of asteroids with orbits that approach or cross the orbit of Earth. These pose the risk of a catastrophic collision with our planet, such as the collision 65 million years ago that killed the dinosaurs.

Earth-Approaching Asteroids

Asteroids that stray far *outside* the main belt are of interest mostly to astronomers. But asteroids that come *inward*, especially those with orbits that come close to or cross the orbit of Earth, are of interest to political leaders, military planners—indeed, everyone alive on Earth. Some of these asteroids briefly become the closest celestial object to us.

In 1994, a 1-kilometer object was picked up passing closer than the Moon, causing a stir of interest in the news media. Today, it is routine to read of small asteroids coming this close to Earth. (They were always there, but only in recent years have astronomers been able to detect such faint objects.)

In 2013, a small asteroid hit our planet, streaking across the sky over the Russian city of Chelyabinsk and exploding with the energy of a nuclear bomb (**Figure 13.13**). The impactor was a stony object about 20 meters in diameter, exploding about 30 kilometers high with an energy of 500 kilotons (about 30 times larger than the nuclear bombs dropped on Japan in World War II). No one was hurt by the blast itself, although it briefly became as bright as the Sun, drawing many spectators to the windows in their offices and homes. When the blast wave from the explosion then reached the town, it blew out the windows. About 1500 people had to seek medical attention from injuries from the shattered glass.

A much larger atmospheric explosion took place in Russia in 1908, caused by an asteroid about 40 meters in diameter, releasing an energy of 5 megatons, as large the most powerful nuclear weapons of today. Fortunately, the area directly affected, on the Tunguska River in Siberia, was unpopulated, and no one was killed. However, the area of forest destroyed by the blast was large equal to the size of a major city (**Figure 13.13**).

Together with any comets that come close to our planet, such asteroids are known collectively as **near-Earth objects (NEOs)**. As we will see (and as the dinosaurs found out 65 million years ago,) the collision of a significant-sized NEO could be a catastrophe for life on our planet.

(a)

(b)

Figure 13.13 Impacts with Earth. (a) As the Chelyabinsk meteor passed through the atmosphere, it left a trail of smoke and briefly became as bright as the Sun. (b) Hundreds of kilometers of forest trees were knocked down and burned at the Tunguska impact site. (credit a: modification of work by Alex Alishevskikh)

LINK TO LEARNING

Visit the **video compilation (https://openstaxcollege.org/l/30vidcomchelmet)** of the Chelyabinsk meteor streaking through the sky over the city on February 15, 2013, as taken by people who were in the area when it occurred.

LINK TO LEARNING

View this **video of a non-technical talk by David Morrison (https://openstaxcollege.org/l/30davmorrison)** to watch "The Chelyabinsk Meteor: Can We Survive a Bigger Impact?" Dr. Morrison (SETI Institute and NASA Ames Research Center) discusses the Chelyabinsk impact and how we learn about NEOs and protect ourselves; the talk is from the Silicon Valley Astronomy Lectures series.

Astronomers have urged that the first step in protecting Earth from future impacts by NEOs must be to learn what potential impactors are out there. In 1998, NASA began the Spaceguard Survey, with the goal to discover and track 90% of Earth-approaching asteroids greater than 1 kilometer in diameter. The size of 1 kilometer was selected to include all asteroids capable of causing global damage, not merely local or regional effects. At 1 kilometer or larger, the impact could blast so much dust into the atmosphere that the sunlight would be dimmed for months, causing global crop failures—an event that could threaten the survival of our civilization. The Spaceguard goal of 90% was reached in 2012 when nearly a thousand of these 1-kilometer **near-Earth asteroids (NEAs)** had been found, along with more than 10,000 smaller asteroids. Figure 13.14 shows how the pace of NEA discoveries has been increasing over recent years.

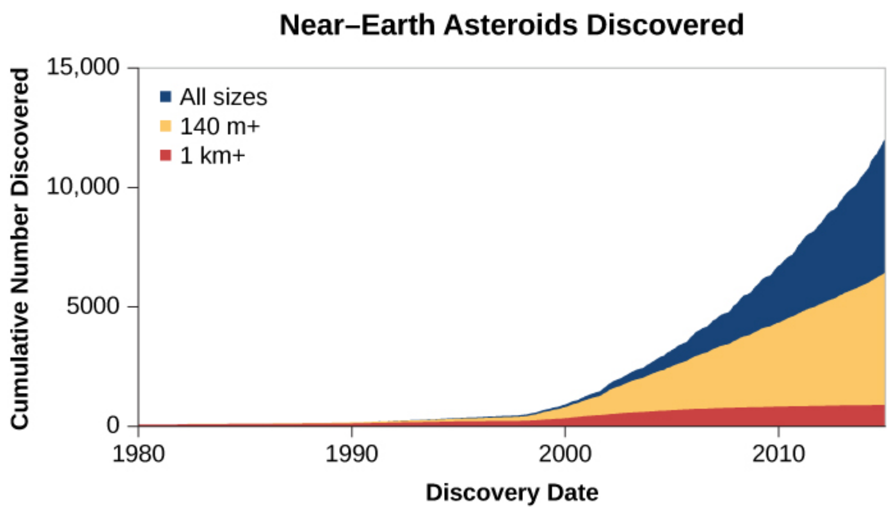


Figure 13.14 Discovery of Near-Earth Asteroids. The accelerating rate of discovery of NEAs is illustrated in this graph, which shows the total number of known NEAs, the number over 140 kilometers in diameter, and the number over 1 kilometer in diameter, the size that poses the dominant impact risk on Earth.

How did astronomers know when they had discovered 90% of these asteroids? There are several ways to estimate the total number, even before they were individually located. One way is to look at the numbers of large craters on the dark lunar maria. Remember that these craters were made by impacts just like the ones we are considering. They are preserved on the Moon's airless surface, whereas Earth soon erases the imprints of past impacts. Thus, the number of large craters on the Moon allows us to estimate how often impacts have occurred on both the Moon and Earth over the past several billion years. The number of impacts is directly related to the number of asteroids and comets on Earth-crossing orbits.

Another approach is to see how often the surveys (which are automated searches for faint points of light that move among the stars) rediscover a previously known asteroid. At the beginning of a survey, all the NEAs it finds will be new. But as the survey becomes more complete, more and more of the moving points the survey cameras record will be *rediscoveries.* The more rediscoveries each survey experiences, the more complete our inventory of these asteroids must be.

We have been relieved to find that none of the NEAs discovered so far is on a trajectory that will impact Earth within the foreseeable future. However, we can't speak for the handful of asteroids larger than 1 kilometer that have not yet been found, or for the much more numerous smaller ones. It is estimated that there are a million NEAs capable of hitting Earth that are smaller than 1 kilometer but still large enough to destroy a city, and our surveys have found fewer than 10% of them. Researchers who work with asteroid orbits estimate that for smaller (and therefore fainter) asteroids we are not yet tracking, we will have about a 5-second warning that one is going to hit Earth—in other words, we won't see it until it enters the atmosphere. Clearly, this estimate gives us a lot of motivation to continue these surveys to track as many asteroids as possible.

Though entirely predictable over times of a few centuries, the orbits of Earth-approaching asteroids are unstable over long time spans as they are tugged by the gravitational attractions of the planets. These objects will eventually meet one of two fates: either they will impact one of the terrestrial planets or the Sun, or they will be ejected gravitationally from the inner solar system due to a near-encounter with a planet. The probabilities of these two outcomes are about the same. The timescale for impact or ejection is only about a hundred million years, very short compared with the 4-billion-year age of the solar system. Calculations show that only approximately one quarter of the current Earth-approaching asteroids will eventually end up colliding with Earth itself.

If most of the current population of Earth-approaching asteroids will be removed by impact or ejection in a hundred million years, there must be a continuing source of new objects to replenish our supply of NEAs. Most of them come from the asteroid belt between Mars and Jupiter, where collisions between asteroids can eject fragments into Earth-crossing orbits (see **Figure 13.15**). Others may be "dead" comets that have exhausted their volatile materials (which we'll discuss in the next section).

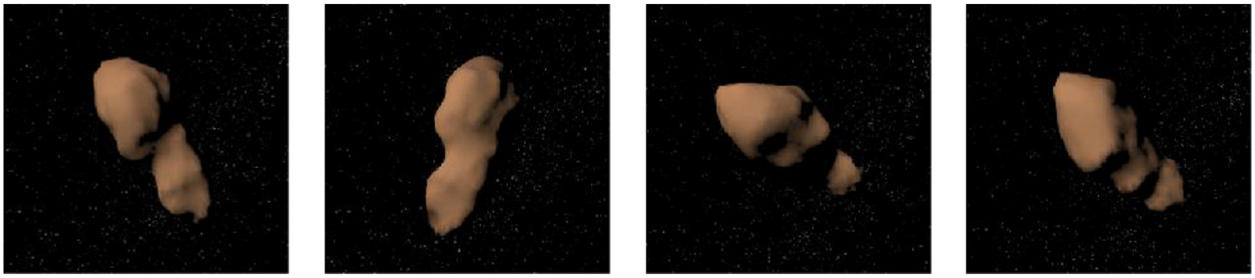


Figure 13.15 Near-Earth Asteroid. Toutatis is a 5-kilometer long NEA that approached within 3 million kilometers of Earth in 1992. This series of images is a reconstruction its size and shape obtained from bouncing radar waves off the asteroid during its close flyby. Toutatis appears to consist of two irregular, lumpy bodies rotating in contact with each other. (Note that the color has been artificially added.) (credit: modification of work by NASA)

One reason scientists are interested in the composition and interior structure of NEAs is that humans will probably need to defend themselves against an asteroid impact someday. If we ever found one of these asteroids on a collision course with us, we would need to deflect it so it would miss Earth. The most straightforward way to deflect it would be to crash a spacecraft into it, either slowing it or speeding it up, slightly changing its orbital period. If this were done several years before the predicted collision, the asteroid would miss the planet entirely—making an asteroid impact the only natural hazard that we could eliminate completely by the application of technology. Alternatively, such deflection could be done by exploding a nuclear bomb near the asteroid to nudge it off course.

To achieve a successful deflection by either technique, we need to know more about the density and interior structure of the asteroid. A spacecraft impact or a nearby explosion would have a greater effect on a solid rocky asteroid such as Eros than on a loose rubble pile. Think of climbing a sand dune compared to climbing a rocky hill with the same slope. On the dune, much of our energy is absorbed in the slipping sand, so the climb is much more difficult and takes more energy.

There is increasing international interest in the problem of asteroid impacts. The United Nations has formed two technical committees on planetary defense, recognizing that the entire planet is at risk from asteroid impacts. However, the fundamental problem remains one of finding NEAs in time for defensive measures to be taken. We must be able to find the next impactor before it finds us. And that's a job for the astronomers.

13.3 THE "LONG-HAIRED" COMETS

Learning Objectives

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

- Characterize the general physical appearance of comets
- Explain the range of cometary orbits
- Describe the size and composition of a typical comet's nucleus
- Discuss the atmospheres of comets
- Summarize the discoveries of the Rosetta mission

Comets differ from asteroids primarily in their icy composition, a difference that causes them to brighten dramatically as they approach the Sun, forming a temporary atmosphere. In some early cultures, these so-called "hairy stars" were considered omens of disaster. Today, we no longer fear comets, but eagerly anticipate those that come close enough to us to put on a good sky show.

Appearance of Comets

A **comet** is a relatively small chunk of icy material (typically a few kilometers across) that develops an atmosphere as it approaches the Sun. Later, there may be a very faint, nebulous **tail**, extending several million kilometers away from the main body of the comet. Comets have been observed from the earliest times: accounts of comets are found in the histories of virtually all ancient civilizations. The typical comet, however, is not spectacular in our skies, instead having the appearance of a rather faint, diffuse spot of light somewhat smaller than the Moon and many times less brilliant. (Comets seemed more spectacular to people before the invention of artificial lighting, which compromises our view of the night sky.)

Like the Moon and planets, comets appear to wander among the stars, slowly shifting their positions in the sky from night to night. Unlike the planets, however, most comets appear at unpredictable times, which perhaps explain why they frequently inspired fear and superstition in earlier times. Comets typically remain visible for periods that vary from a couple of weeks to several months. We'll say more about what they are made of and how they become visible after we discuss their motions.

Note that still images of comets give the impression that they are moving rapidly across the sky, like a bright meteor or shooting star. Looking only at such images, it is easy to confuse comets and meteors. But seen in the real sky, they are very different: the meteor burns up in our atmosphere and is gone in a few seconds, whereas the comet may be visible for weeks in nearly the same part of the sky.

Comet Orbits

The study of comets as members of the solar system dates from the time of Isaac Newton, who first suggested that they orbited the Sun on extremely elongated ellipses. Newton's colleague Edmund Halley (see the **Edmund Halley: Astronomy's Renaissance Man** feature box) developed these ideas, and in 1705, he published calculations of 24 comet orbits. In particular, he noted that the orbits of the bright comets that had appeared in the years 1531, 1607, and 1682 were so similar that the three could well be the same comet, returning to perihelion (closest approach to the Sun) at average intervals of 76 years. If so, he predicted that the object should next return about 1758. Although Halley had died by the time the comet appeared as he predicted, it was given the name Comet Halley (rhymes with "valley") in honor of the astronomer who first recognized it as a permanent member of our solar system, orbiting around the Sun. Its aphelion (furthest point from the Sun) is beyond the orbit of Neptune.

We now know from historical records that Comet Halley has actually been observed and recorded on every passage near the Sun since 239 BCE at intervals ranging from 74 to 79 years. The period of its return varies somewhat because of orbital changes produced by the pull of the giant planets. In 1910, Earth was brushed by the comet's tail, causing much needless public concern. Comet Halley last appeared in our skies in 1986 (**Figure 13.16**), when it was met by several spacecraft that gave us a wealth of information about its makeup; it will return in 2061.

Figure 13.16 Comet Halley. This composite of three images (one in red, one in green, one in blue) shows Comet Halley as seen with a large telescope in Chile in 1986. During the time the three images were taken in sequence, the comet moved among the stars. The telescope was moved to keep the image of the comet steady, causing the stars to appear in triplicate (once in each color) in the background. (credit: modification of work by ESO)

VOYAGERS IN ASTRONOMY

Edmund Halley: Astronomy's Renaissance Man

Edmund Halley (**Figure 13.17**), a brilliant astronomer who made contributions in many fields of science and statistics, was by all accounts a generous, warm, and outgoing person. In this, he was quite the opposite of his good friend Isaac Newton, whose great work, the *Principia* (see **Orbits and Gravity**), Halley encouraged, edited, and helped pay to publish. Halley himself published his first scientific paper at age 20, while still in college. As a result, he was given a royal commission to go to Saint Helena (a remote island off the coast of Africa where Napoleon would later be exiled) to make the first telescopic survey of the southern sky. After returning, he received the equivalent of a master's degree and was elected to the prestigious Royal Society in England, all at the age of 22.

In addition to his work on comets, Halley was the first astronomer to recognize that the so-called "fixed" stars move relative to each other, by noting that several bright stars had changed their positions since Ptolemy's publication of the ancient Greek catalogs. He wrote a paper on the possibility of an infinite universe, proposed that some stars may be variable, and discussed the nature and size of *nebulae* (glowing cloudlike structures visible in telescopes). While in Saint Helena, Halley observed the planet

Mercury going across the face of the Sun and developed the mathematics of how such transits could be used to establish the size of the solar system.

In other fields, Halley published the first table of human life expectancies (the precursor of life-insurance statistics); wrote papers on monsoons, trade winds, and tides (charting the tides in the English Channel for the first time); laid the foundations for the systematic study of Earth's magnetic field; studied evaporation and how inland waters become salty; and even designed an underwater diving bell. He served as a British diplomat, advising the emperor of Austria and squiring the future czar of Russia around England (avidly discussing, we are told, both the importance of science and the quality of local brandy).

In 1703, Halley became a professor of geometry at Oxford, and in 1720, he was appointed Astronomer Royal of England. He continued observing Earth and the sky and publishing his ideas for another 20 years, until death claimed him at age 85.

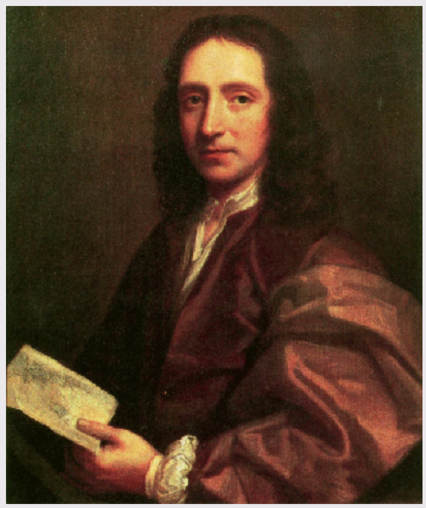


Figure 13.17 Edmund Halley (1656–1742). Halley was a prolific contributor to the sciences. His study of comets at the turn of the eighteenth century helped predict the orbit of the comet that now bears his name.

Only a few comets return in a time measureable in human terms (shorter than a century), like Comet Halley does; these are called *short-period* comets. Many short-period comets have had their orbits changed by coming too close to one of the giant planets—most often Jupiter (and they are thus sometimes called Jupiter-family comets). Most comets have long periods and will take thousands of years to return, if they return at all. As we will see later in this chapter, most Jupiter-family comets come from a different source than the *long-period* comets (those with orbital periods longer than about a century).

Observational records exist for thousands of comets. We were visited by two bright comets in recent decades. First, in March 1996, came Comet Hyakutake, with a very long tail. A year later, Comet Hale-Bopp appeared; it was as bright as the brightest stars and remained visible for several weeks, even in urban areas (see the image that opens this chapter, **Figure 13.1**).

Table 13.2 lists some well-known comets whose history or appearance is of special interest.

Some Interesting Comets

Name	Period	Significance
Great Comet of 1577	Long	Tycho Brahe showed it was beyond the Moon (a big step in our understanding)
Great Comet of 1843	Long	Brightest recorded comet; visible in daytime
Daylight Comet of 1910	Long	Brightest comet of the twentieth century
West	Long	Nucleus broke into pieces (1976)
Hyakutake	Long	Passed within 15 million km of Earth (1996)
Hale–Bopp	Long	Brightest recent comet (1997)
Swift-Tuttle	133 years	Parent comet of Perseid meteor shower
Halley	76 years	First comet found to be periodic; explored by spacecraft in 1986
Borrelly	6.8 years	Flyby by Deep Space 1 spacecraft (2000)
Biela	6.7 years	Broke up in 1846 and not seen again
Churyumov-Gerasimenko	6.5 years	Target of Rosetta mission (2014–16)
Wild 2	6.4 years	Target of Stardust sample return mission (2004)
Tempel 1	5.7 years	Target of Deep Impact mission (2005)
Encke	3.3 years	Shortest known period

Table 13.2

The Comet's Nucleus

When we look at an active comet, all we normally see is its temporary atmosphere of gas and dust illuminated by sunlight. This atmosphere is called the comet's head or *coma.* Since the gravity of such small bodies is very weak, the atmosphere is rapidly escaping all the time; it must be replenished by new material, which has to come from somewhere. The source is the small, solid **nucleus** inside, just a few kilometers across, usually hidden by the glow from the much-larger atmosphere surrounding it. The nucleus is the real comet, the fragment of ancient icy material responsible for the atmosphere and the tail (Figure 13.18).

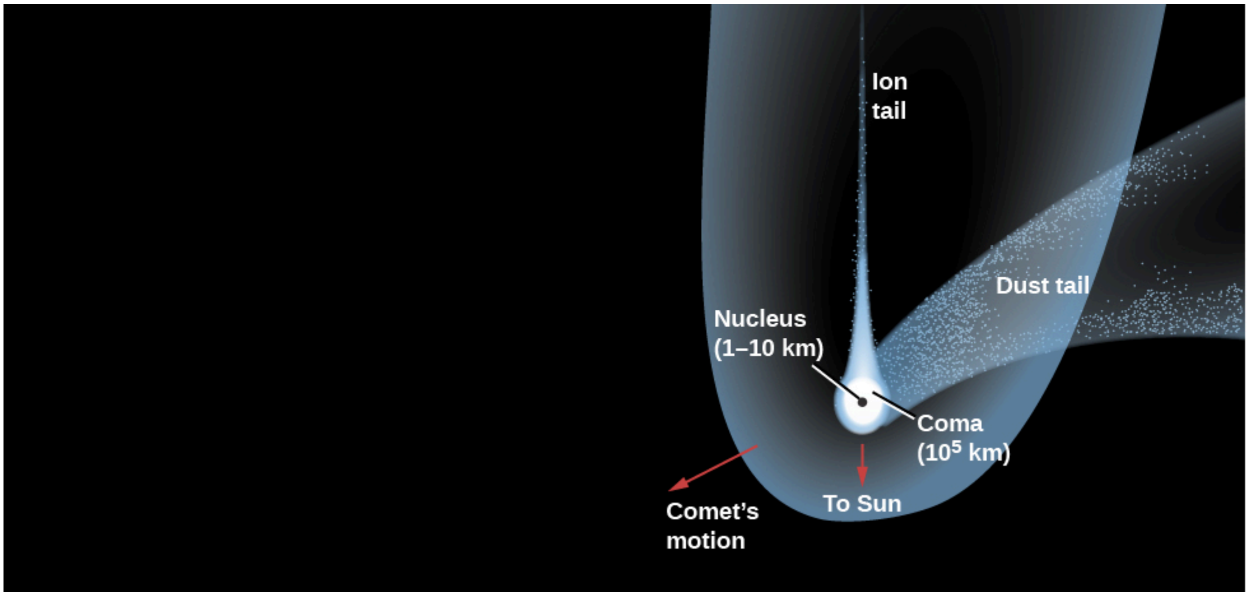


Figure 13.18 Parts of a Comet. This schematic illustration shows the main parts of a comet. Note that the different structures are not to scale.

The modern theory of the physical and chemical nature of comets was first proposed by Harvard astronomer Fred Whipple in 1950. Before Whipple's work, many astronomers thought that a comet's nucleus might be a loose aggregation of solids, sort of an orbiting "gravel bank," Whipple proposed instead that the nucleus is a solid object a few kilometers across, composed in substantial part of water ice (but with other ices as well) mixed with silicate grains and dust. This proposal became known as the "dirty snowball" model.

The water vapor and other volatiles that escape from the nucleus when it is heated can be detected in the comet's head and tail, and therefore, we can use spectra to analyze what atoms and molecules the nucleus ice consists of. However, we are somewhat less certain of the non-icy component. We have never identified a fragment of solid matter from a comet that has survived passage through Earth's atmosphere. However, spacecraft that have approached comets have carried dust detectors, and some comet dust has even been returned to Earth (see **Figure 13.19**). It seems that much of the "dirt" in the dirty snowball is dark, primitive hydrocarbons and silicates, rather like the material thought to be present on the dark, primitive asteroids.

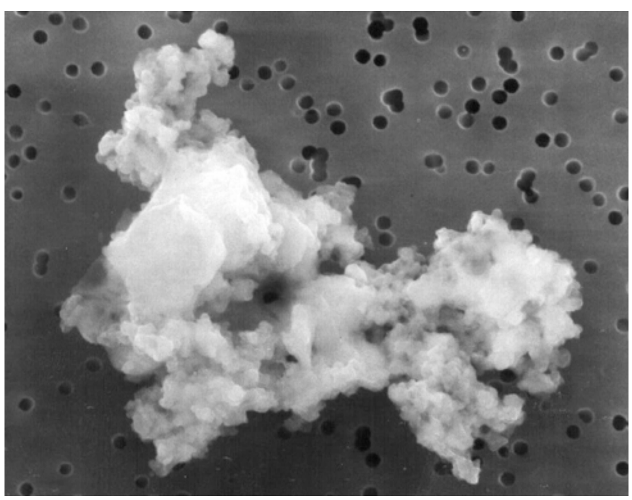


Figure 13.19 Captured Comet Dust. This particle (seen through a microscope) is believed to be a tiny fragment of cometary dust, collected in the upper atmosphere of Earth. It measures about 10 microns, or 1/100 of a millimeter, across. (credit: NASA/JPL)

Since the nuclei of comets are small and dark, they are difficult to study from Earth. Spacecraft did obtain direct measurements of a comet nucleus, however, in 1986, when three spacecraft swept past Comet Halley at close range (see **Figure 13.20**). Subsequently, other spacecraft have flown close to other comets. In 2005, the NASA *Deep Impact* spacecraft even carried a probe for a high-speed impact with the nucleus of Comet Tempel 1. But by far, the most productive study of a comet has been by the 2015 Rosetta mission, which we will discuss shortly.

Figure 13.20 Close-up of Comet Halley. This historic photograph of the black, irregularly shaped nucleus of Comet Halley was obtained by the ESA *Giotto* spacecraft from a distance of about 1000 kilometers. The bright areas are jets of material escaping from the surface. The length of the nucleus is 10 kilometers, and details as small as 1 kilometer can be made out. (credit: modification of work by ESA)

The Comet's Atmosphere

The spectacular activity that allows us to see comets is caused by the evaporation of cometary ices heated by sunlight. Beyond the asteroid belt, where comets spend most of their time, these ices are solidly frozen. But as a comet approaches the Sun, it begins to warm up. If water (H_2O) is the dominant ice, significant quantities vaporize as sunlight heats the surface above 200 K. This happens for the typical comet somewhat beyond the orbit of Mars. The evaporating H_2O in turn releases the dust that was mixed with the ice. Since the comet's nucleus is so small, its gravity cannot hold back either the gas or the dust, both of which flow away into space at speeds of about 1 kilometer per second.

The comet continues to absorb energy as it approaches the Sun. A great deal of this energy goes into the evaporation of its ice, as well as into heating the surface. However, recent observations of many comets indicate that the evaporation is not uniform and that most of the gas is released in sudden spurts, perhaps confined to a few areas of the surface. Expanding into space at a speed of about 1 kilometer per second, the comet's atmosphere can reach an enormous size. The diameter of a comet's head is often as large as Jupiter, and it can sometimes approach a diameter of a million kilometers (**Figure 13.21**).

Figure 13.21 Head of Comet Halley. Here we see the cloud of gas and dust that make up the head, or coma, of Comet Halley in 1986. On this scale, the nucleus (hidden inside the cloud) would be a dot too small to see. (credit: modification of work by NASA/W. Liller)

Most comets also develop tails as they approach the Sun. A comet's tail is an extension of its atmosphere, consisting of the same gas and dust that make up its head. As early as the sixteenth century, observers realized that comet tails always point away from the Sun (Figure 13.22), not back along the comet's orbit. Newton proposed that comet tails are formed by a repulsive force of sunlight driving particles away from the head—an idea close to our modern view.

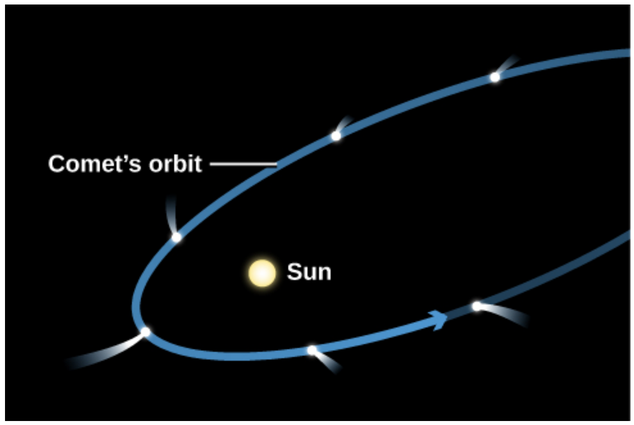
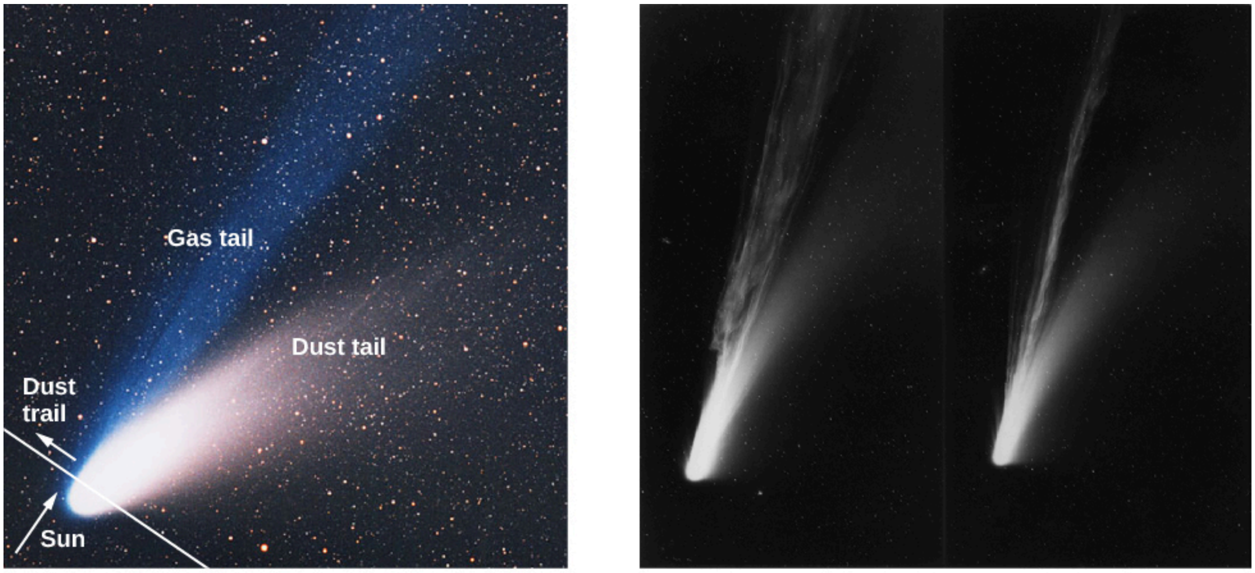


Figure 13.22 Comet Orbit and Tail. The orientation of a typical comet tail changes as the comet passes perihelion. Approaching the Sun, the tail is behind the incoming comet head, but on the way out, the tail precedes the head.

The two different components that make up the tail (the dust and gas) act somewhat differently. The brightest part of the tail is called the *dust tail*, to differentiate it from a fainter, straight tail made of ionized gas, called the ion tail. The ion tail is carried outward by streams of ions (charged particles) emitted by the Sun. As you can see in Figure 13.23, the smoother dust tail curves a bit, as individual dust particles spread out along the comet's orbit, whereas the straight ion is tail pushed more directly outward from the Sun by our star's wind of charged particles



(a) (b)

Figure 13.23 Comet Tails. (a) As a comet nears the Sun, its features become more visible. In this illustration from NASA showing Comet Hale-Bopp, you can see a comet's two tails: the more easily visible dust tail, which can be up to 10 million kilometers long, and the fainter gas tail (or ion tail), which is up to hundreds of millions of kilometers long. The grains that make up the dust tail are the size of smoke particles. (b) Comet Mrkos was photographed in 1957 with a wide-field telescope at Palomar Observatory and also shows a clear distinction between the straight gas tail and the curving dust tail. (credit a: modification of work by ESO/E. Slawik; credit b: modification of work by Charles Kearns, George O. Abell, and Byron Hill)

LINK TO LEARNING

These days, comets close to the Sun can be found with spacecraft designed to observe our star. For example, in early July, 2011, astronomers at the ESA/NASA's Solar and Heliospheric Observatory (SOHO) witnessed a **comet (https://openstaxcollege.org/l/30ESANASAcomet)** streaking toward the Sun, one of almost 3000 such sightings. You can also watch a brief video by NASA entitled "Why Are We Seeing So Many Sungrazing Comets?"

The Rosetta Comet Mission

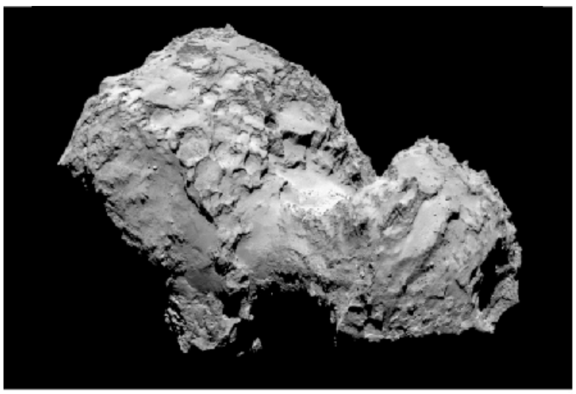
In the 1990s, European scientists decided to design a much more ambitious mission that would match orbits with an incoming comet and follow it as it approached the Sun. They also proposed that a smaller spacecraft would actually try to land on the comet. The 2-ton main spacecraft was named *Rosetta*, carrying a dozen scientific instruments, and its 100-kilogram lander with nine more instruments was named *Philae*.

The Rosetta mission was launched in 2004. Delays with the launch rocket caused it to miss its original target comet, so an alternate destination was picked, Comet Churyumov-Gerasimenko (named after the two discoverers, but generally denoted 67P). This comet's period of revolution is 6.45 years, making it a Jupiter-family comet.

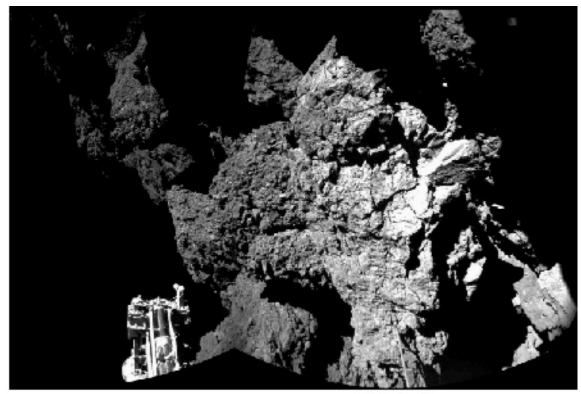
Since the European Space Agency did not have access to the plutonium-fueled nuclear power sources used by NASA for deep space missions, *Rosetta* had to be solar powered, requiring especially large solar panels. Even these were not enough to keep the craft operating as it matched orbits with 67P near the comet's aphelion. The only solution was to turn off all the spacecraft systems and let it coast for several years toward the Sun, out of contact with controllers on Earth until solar energy was stronger. The success of the mission depended on an automatic timer to turn the power back on as it neared the Sun. Fortunately, this strategy worked.

In August 2014, *Rosetta* began a gradual approach to the comet nucleus, which is a strangely misshapen object about 5 kilometers across, quite different from the smooth appearance of Halley's nucleus (but equally dark). Its rotation period is 12 hours. On November 12, 2014, the *Philae* lander was dropped, descending slowly for 7 hours before gently hitting the surface. It bounced and rolled, coming to rest under an overhang where there was not enough sunlight to keep its batteries charged. After operating for a few hours and sending data back to the orbiter, *Philae* went silent. The main *Rosetta* spacecraft continued operations, however, as the level of comet activity increased, with steamers of gas jetting from the surface. As the comet approached perihelion in September 2015, the spacecraft backed off to ensure its safety.

The extent of the *Rosetta* images (and data from other instruments) far exceeds anything astronomers had seen before from a comet. The best imaging resolution was nearly a factor of 100 greater than in the best Halley images. At this scale, the comet appears surprisingly rough, with sharp angles, deep pits, and overhangs (**Figure 13.24**).



(a)



(b)

Figure 13.24 Comet 67P's Strange Shape and Surface Features. (a) This image from the *Rosetta* camera was taken from a distance of 285 kilometers. The resolution is 5 meters. You can see that the comet consists of two sections with a connecting "neck" between them. (b) This close-up view of Comet Churyumov-Gerasimenko is from the *Philae* lander. One of the lander's three feet is visible in the foreground. The lander itself is mostly in shadow. (credit a: modification of work by ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; credit b: modification of work by ESA/Rosetta/Philae/CIVA)

The double-lobed shape of 67P's nucleus has been tentatively attributed to the collision and merger of two independent comet nuclei long ago. The spacecraft verified that the comet's dark surface was covered with organic carbon-rich compounds, mixed with sulfides and iron-nickel grains. 67P has an average density of only 0.5 g/cm^3 (recall water in these units has a density of 1 g/cm^3.) This low density indicates that the comet is quite porous, that is, there is a large amount of empty space among its materials.

We already knew that the evaporation of comet ices was sporadic and limited to small jets, but in comet 67P, this was carried to an extreme. At any one time, more than 99% of the surface is inactive. The active vents are only a few meters across, with the material confined to narrow jets that persist for just a few minutes (**Figure 13.25**). The level of activity is strongly dependent on solar heating, and between July and August 2015, it increased by a factor of 10. Isotopic analysis of deuterium in the water ejected by the comet shows that it is different from the water found on Earth. Thus, apparently comets like 67P did not contribute to the origin of our oceans or the water in our bodies, as some scientists had thought.

Figure 13.25 Gas Jets on Comet 67P. (a) This activity was photographed by the *Rosetta* spacecraft near perihelion. You can see a jet suddenly appearing; it was active for only a few minutes. (b) This spectacular photo, taken near perihelion, shows the active comet surrounded by multiple jets of gas and dust. (credit a, b: modification of work by ESA/Rosetta/MPS; credit c: modification of work by ESA/Rosetta/NAVCAM)

LINK TO LEARNING

The European Space Agency is continuing to make **interesting short videos (https://openstaxcollege.org/l/30ESAvideoros)** illustrating the challenges and results of the Rosetta and Philae missions. For example, watch "*Rosetta*'s Moment in the Sun" to see some of the images of the comet generating plumes of gas and dust and hear about some of the dangers an active comet poses for the spacecraft.

13.4 THE ORIGIN AND FATE OF COMETS AND RELATED OBJECTS

Learning Objectives

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

- Describe the traits of the centaur objects
- Chronicle the discovery and describe the composition of the Oort cloud
- Describe trans-Neptunian and Kuiper-belt objects
- Explain the proposed fate of comets that enter the inner solar system

The comets we notice when they come near Earth (especially the ones coming for the first time) are probably the most primitive objects we can study, preserved unchanged for billions of years in the deep freeze of the outer solar system. However, astronomers have discovered many other objects that orbit the Sun beyond the planets.

Centaurs

In the outer solar system, where most objects contain large amounts of water ice, the distinction between asteroids and comets breaks down. Astronomers initially still used the name "asteroids" for new objects discovered going around the Sun with orbits that carry them far beyond Jupiter. The first of these objects is Chiron, found in 1977 on a path that carries it from just inside the orbit of Saturn at its closest approach to the Sun out to almost the distance of Uranus (**Figure 13.26**). The diameter of Chiron is estimated to be about 200 kilometers, much larger than any known comet.

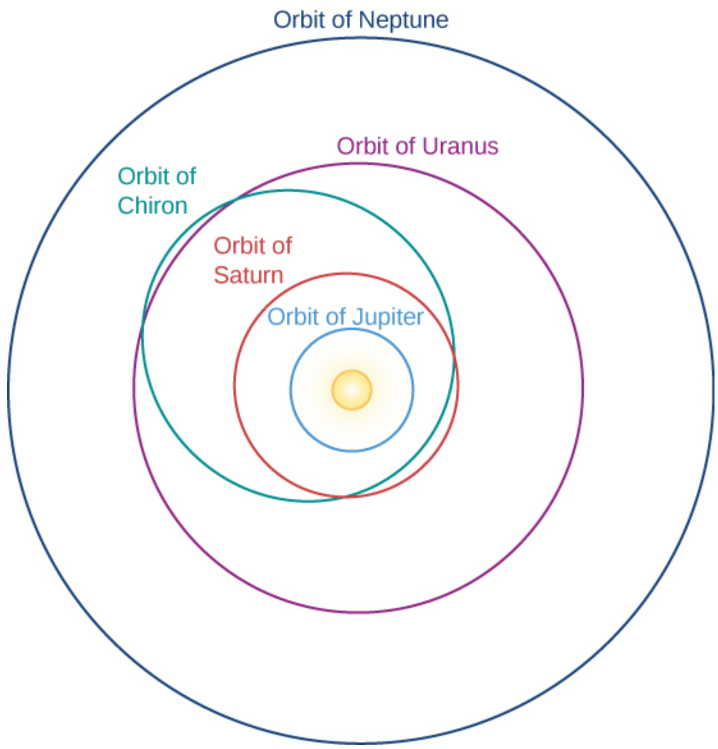


Figure 13.26 Chiron's Orbit. Chiron orbits the Sun every 50 years, with its closest approach being inside the orbit of Saturn and its farthest approach out to the orbit of Uranus.

In 1992, a still-more-distant object named Pholus was discovered with an orbit that takes it 33 AU from the Sun, beyond the orbit of Neptune. Pholus has the reddest surface of any object in the solar system, indicating a strange (and still unknown) surface composition. As more objects are discovered in these distant reaches, astronomers decided that they will be given the names of *centaurs* from classical mythology; this is because the centaurs were half human, half horse, and these new objects display some of the properties of both asteroids and comets.

Beyond the orbit of Neptune lies a cold, dark realm populated by objects called simply trans-Neptunian objects (TNOs). The first discovered, and best known, of these TNOs is the dwarf planet Pluto. We discussed Pluto and the New Horizons spacecraft encounter with it in **Rings, Moons, and Pluto**. The second TNO was discovered in 1992, and now more than a thousand are known, most of them smaller than Pluto.

The largest ones after Pluto—named Eris, Makemake, and Haumea—are also classed as dwarf planets. Except for their small size, dwarf planets have many properties in common with the larger planets. Pluto has five moons, and two moons have been discovered orbiting Haumea and one each circling Eris and Makemake.

The Kuiper Belt and the Oort Cloud

TNOs are a part of what is called the **Kuiper belt**, a large area of space beyond Neptune that is also the source of many comets. Astronomers study the Kuiper belt in two ways. New, more powerful telescopes allow us to discover many of the larger members of the Kuiper belt directly. We can also measure the composition of comets that come from the Kuiper belt. More than a thousand Kuiper belt objects have been discovered, and astronomers estimate that there are more than 100,000 with diameters large than 100 kilometers, in a disk extending out to about 50 AU from the Sun.

The short-period comets are thought to originate in the Kuiper belt, where small gravitational perturbations from Neptune can gradually shift their orbits until they can penetrate the inner solar system. The long-period comets, however, come from a much more distant reservoir of icy objects, called the Oort cloud.

Careful studies of the orbits of long-period comets revealed that they come initially from very great distances. By following their orbits backward, we can calculate that the *aphelia* (points farthest from the Sun) of newly discovered comets typically have values near 50,000 AU (more than a thousand times farther than Pluto). This clustering of aphelion distances was first noted by Dutch astronomer Jan Oort, who, in 1950, proposed an idea for the origin of those comets that is still accepted today (**Figure 13.27**).

Figure 13.27 Jan Oort (1900–1992). Jan Oort first suggested that there might be a reservoir of frozen chunks, potential comet nuclei, at the edge of the region of the Sun's gravitational influence. (credit: The Leiden Observatory)

It is possible to calculate that a star's gravitational *sphere of influence*—the distance within which it can exert sufficient gravitation to hold onto orbiting objects—is about one third of its distance to the nearest other stars. Stars in the vicinity of the Sun are spaced in such a way that the Sun's sphere of influence extends a little beyond 50,000 AU, or about 1 light-year. At such great distances, however, objects in orbit about the Sun can be perturbed by the gravity of passing stars. Some of the perturbed objects can then take on orbits that bring them much closer to the Sun (while others might be lost to the solar system forever).

Oort suggested, therefore, that the new comets we were seeing were examples of objects orbiting the Sun near the edge of its sphere of influence, whose orbits had been disturbed by nearby stars, eventually bringing them close to the Sun where we can see them. The reservoir of ancient icy objects from which such comets are derived is now called the **Oort cloud**.

Astronomers estimate that there are about a trillion (10^{12}) comets in the Oort cloud. In addition, we estimate that about 10 times this number of icy objects could be orbiting the Sun in the volume of space between the Kuiper belt (which is gravitationally linked to Neptune) and the Oort cloud. These objects remain undiscovered because they are too faint to be seen directly and their orbits are too stable to permit any of them to be deflected inward close to the Sun. The total number of icy or cometary objects in the outer reaches of our solar system could thus be on the order of 10 trillion (10^{13}), a very large number indeed.

What is the mass represented by 10^{13} comets? We can make an estimate if we assume something about comet sizes and masses. Let us suppose that the nucleus of Comet Halley is typical. Its observed volume is about 600 km^3. If the primary constituent is water ice with a density of about 1 g/cm^3, then the total mass of Halley's nucleus must be about 6×10^{14} kilograms. This is about one ten billionth (10^{-10}) of the mass of Earth.

If our estimate is reasonable and there are 10^{13} comets with this mass out there, their total mass would be equal to about 1000 Earths—comparable to the mass of all the planets put together. Therefore, icy, cometary material could be the most important constituent of the solar system after the Sun itself.

EXAMPLE 13.1

Mass of the Oort Cloud Comets

Suppose the Oort cloud contains 10^{12} comets with an average diameter of 10 km each. Let's estimate the mass of the total Oort cloud.

Solution

We can start by assuming that typical comets are about the size of Comets Halley and Borrelly, with a diameter of 10 km and a density appropriate to water ice, which is about 1 g/cm^3 or 1000 kg/m^3. We know that density = mass/volume, the volume of a sphere, $V = \frac{4}{3}\pi R^3$, and the radius, $R = \frac{1}{2}D$.

Therefore, for each comet,

$$\begin{aligned} \text{mass} &= \text{density} \times \text{volume} \\ &= \text{density} \times \frac{4}{3}\pi\left(\frac{1}{2}D\right)^3 \end{aligned}$$

Given that 10 km = 10^4 m, each comet's mass is

$$\begin{aligned} \text{mass} &= 1000\ \text{kg/m}^3 \times \frac{4}{3} \times 3.14 \times \frac{1}{8} \times \left(10^4\right)^3\ \text{m}^3 \\ &\approx 10^{15}\ \text{kg} \\ &= 10^{12}\ \text{tons} \end{aligned}$$

To calculate the total mass of the cloud, we multiply this typical mass for one comet by the number of comets:

$$\begin{aligned} \text{total mass} &= 10^{15}\ \text{kg/comet} \times 10^{12}\ \text{comets} \\ &= 10^{27}\ \text{kg} \end{aligned}$$

Check Your Learning

How does the total mass we calculated above compare to the mass of Jupiter? To the mass of the Sun? (Give a numerical answer.)

Answer:

The mass of Jupiter is about 1.9 × 10^{27} kg. The mass of the Oort cloud calculated above is 10^{27} kg. So the cloud would contain about half a Jupiter of mass. The mass of the Sun is 2 × 10^{30} kg. This means the Oort cloud would be

$$\frac{10^{27}\ \text{kg}}{\left(2 \times 10^{30}\ \text{kg}\right)} = 0.0005 \times \text{the mass of the Sun}$$

Early Evolution of the Planetary System

Comets from the Oort cloud help us sample material that formed very far from the Sun, whereas the short-period comets from the Kuiper belt sample materials that were planetesimals in the solar nebula disk but did not form planets. Studies of the Kuiper belt also are influencing our understanding of the early evolution of our planetary system.

The objects in the Oort cloud and the Kuiper belt have different histories, and they may therefore have different compositions. Astronomers are therefore very interested in comparing detailed measurements of the comets derived from these two source regions. Most of the bright comets that have been studied in the past (such as Hyakutake and Hale-Bopp) are Oort cloud comets, but P67 and several other comets targeted for spacecraft measurements in the next decade are Jupiter-family comets from the Kuiper belt (see **Table 13.2**).

The Kuiper belt is made up of ice-and rock planetesimals, a remnant of the building blocks of the planets. Since it is gravitationally linked to Neptune, it can help us understand the formation and history of the solar system. As the giant planets formed, their gravity profoundly influenced the orbits of Kuiper belt objects. Computer simulations of the early evolution of the planetary system suggest that the gravitational interactions between the giant planets and the remaining planetesimals caused the orbit of Jupiter to drift inward, whereas the orbits of Saturn, Uranus, and Neptune all expanded, carrying the Kuiper belt with them.

Another hypotheses involves a fifth giant planet that was expelled from the solar system entirely as the planetary orbits shifted. Neptune’s retrograde (backward-orbiting) moon Triton (which is nearly as large as Pluto) may have been a Kuiper belt object captured by Neptune during the period of shifting orbits. It clearly seems that the Kuiper belt may carry important clues to the way our solar system reached its present planetary configuration.

MAKING CONNECTIONS

Comet Hunting as a Hobby

When amateur astronomer David Levy (**Figure 13.28**), the co-discoverer of Comet Shoemaker-Levy 9, found his first comet, he had already spent 928 fruitless hours searching through the dark night sky. But the discovery of the first comet only whetted his appetite. Since then, he has found 8 others on his own and 13 more working with others. Despite this impressive record, he ranks only third in the record books for number of comet discoveries. But David hopes to break the record someday.

All around the world, dedicated amateur observers spend countless nights scanning the sky for new comets. Astronomy is one of the very few fields of science where amateurs can still make a meaningful contribution, and the discovery of a comet is one of the most exciting ways they can establish their place in astronomical history. Don Machholz, a California amateur (and comet hunter) who has been making a study of comet discoveries, reported that between 1975 and 1995, 38% of all comets discovered were found by amateurs. Those 20 years yielded 67 comets for amateurs, or almost 4 per year. That might sound pretty encouraging to new comet hunters, until they learn that the average number of hours the typical amateur spent searching for a comet before finding one was about 420. Clearly, this is not an activity for impatient personalities.

What do comet hunters do if they think they have found a new comet? First, they must check the object’s location in an atlas of the sky to make sure it really is a comet. Since the first sighting of a comet usually occurs when it is still far from the Sun and before it sports a significant tail, it will look like only a small, fuzzy patch. And through most amateur telescopes, so will nebulae (clouds of cosmic gas and dust) and galaxies (distant groupings of stars). Next, they must check that they have not come across a comet that is already known, in which case, they will only get a pat on the back instead of fame and glory. Then they must re-observe or re-image it sometime later to see whether its motion in the sky is appropriate for comets.

Often, comet hunters who think they have made a discovery get another comet hunter elsewhere in the country to confirm it. If everything checks out, the place they contact is the Central Bureau for Astronomical Telegrams at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts (http://www.cbat.eps.harvard.edu/). If the discovery is confirmed, the bureau will send the news out to astronomers and observatories around the world. One of the unique rewards of comet hunting is that the discoverer's name becomes associated with the new comet—a bit of cosmic fame that few hobbies can match.

Figure 13.28 David Levy. Amateur astronomer David Levy ranks third in the world for comet discoveries. (credit: Andrew Fraknoi)

The Fate of Comets

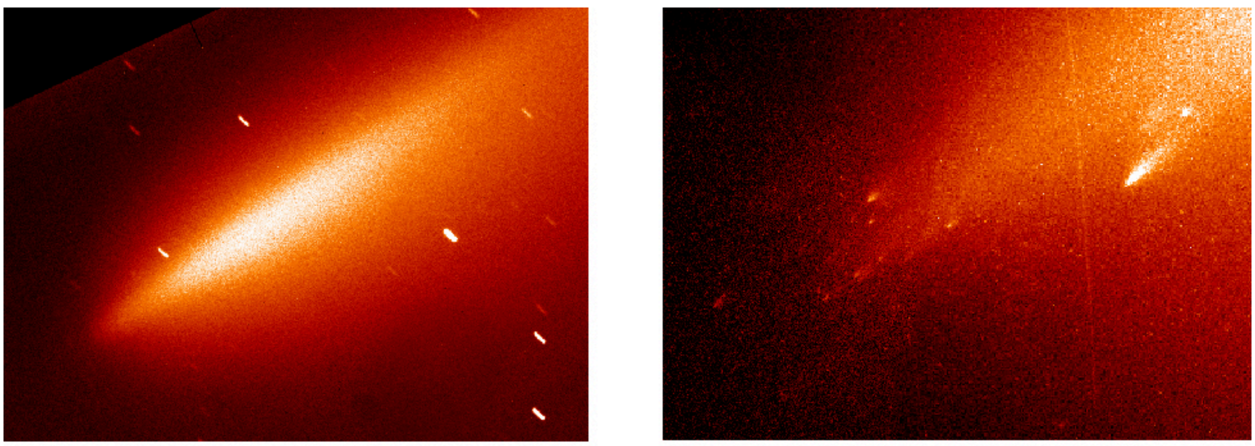
Any comet we see today will have spent nearly its entire existence in the Oort cloud or the Kuiper belt at a temperature near absolute zero. But once a comet enters the inner solar system, its previously uneventful life history begins to accelerate. It may, of course, survive its initial passage near the Sun and return to the cold reaches of space where it spent the previous 4.5 billion years. At the other extreme, it may collide with the Sun or come so close that it is destroyed on its first perihelion passage (several such collisions have been observed with space telescopes that monitor the Sun). Sometimes, however, the new comet does not come that close to the Sun but instead interacts with one or more of the planets.

LINK TO LEARNING

SOHO (the Solar and Heliospheric Observatory) has an **excellent collection of videos of comets (https://openstaxcollege.org/l/30SOHOcomvid)** that come near the Sun. At this site, comet ISON approaches the Sun and is believed to be destroyed in its passage.

A comet that comes within the gravitational influence of a planet has three possible fates. It can (1) impact the planet, ending the story at once; (2) speed up and be ejected, leaving the solar system forever; or (3) be perturbed into an orbit with a shorter period. In the last case, its fate is sealed. Each time it approaches the Sun, it loses part of its material and also has a significant chance of collision with a planet. Once the comet is in this kind of short-period orbit, its lifetime starts being measured in thousands, not billions, of years.

A few comets end their lives catastrophically by breaking apart (sometimes for no apparent reason) (**Figure 13.29**). Especially spectacular was the fate of the faint Comet Shoemaker-Levy 9, which broke into about 20 pieces when it passed close to Jupiter in July 1992. The fragments of Shoemaker-Levy were actually captured into a very elongated, two-year orbit around Jupiter, more than doubling the number of known jovian moons. This was only a temporary enrichment of Jupiter's family, however, because in July 1994, all the comet fragments crashed unto Jupiter, releasing energy equivalent to millions of megatons of TNT.



(a) (b)

Figure 13.29 Breakup of Comet LINEAR. (a) A ground-based view with much less detail and (b) a much more detailed photo with the Hubble Space Telescope, showing the multiple fragments of the nucleus of Comet LINEAR. The comet disintegrated in July 2000 for no apparent reason. (Note in the left view, the fragments all blend their light together, and can't be distinguished. The short diagonal white lines are stars that move in the image, which is keeping track of the moving comet.) (credit a: modification of work by the University of Hawaii; credit b: modification of work by NASA, Harold Weaver (the Johns Hopkins University), and the HST Comet LINEAR Investigation Team)

As each cometary fragment streaked into the jovian atmosphere at a speed of 60 kilometers per second, it disintegrated and exploded, producing a hot fireball that carried the comet dust as well as atmospheric gases to high altitudes. These fireballs were clearly visible in profile, with the actual point of impact just beyond the jovian horizon as viewed from Earth (**Figure 13.30**). As each explosive plume fell back into Jupiter, a region of the upper atmosphere larger than Earth was heated to incandescence and glowed brilliantly for about 15 minutes, a glow we could detect with infrared-sensitive telescopes.

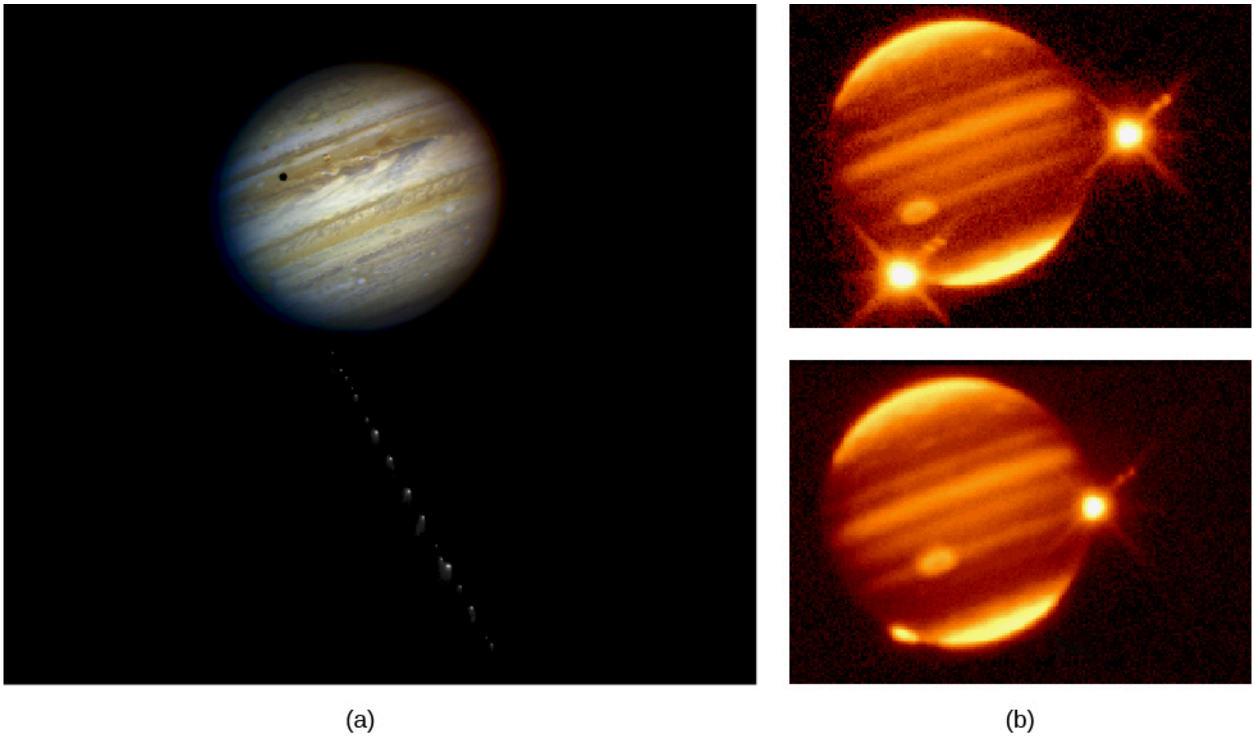


Figure 13.30 Comet Impact on Jupiter. (a) The “string” of white objects are fragments of Comet Shoemaker-Levy 9 approaching Jupiter. (b) The first fragment of the comet impacts Jupiter, with the point of contact on the bottom left side in this image. On the right is Jupiter’s moon, Io. The equally bright spot in the top image is the comet fragment flaring to maximum brightness. The bottom image, taken about 20 minutes later, shows the lingering flare from the impact. The Great Red Spot is visible near the center of Jupiter. These infrared images were taken with a German-Spanish telescope on Calar Alto in southern Spain. (credit a: modification of work by ESA; credit b: modification of work by Tom Herbst, Max-Planck-Institut fuer Astronomie, Heidelberg, Doug Hamilton, Max-Planck-Institut fuer Kernphysik, Heidelberg, Hermann Boehnhardt, Universitaets-Sternewarte, Muenchen, and Jose Luis Ortiz Moreno, Instituto de Astrofisica de Andalucia, Granada)

After this event, dark clouds of debris settled into the stratosphere of Jupiter, producing long-lived “bruises” (each still larger than Earth) that could be easily seen through even small telescopes (**Figure 13.31**). Millions of people all over the world peered at Jupiter through telescopes or followed the event via television or online. Another impact feature was seen on Jupiter in summer 2009, indicating that the 1994 events were by no means unique. Seeing these large, impact explosions on Jupiter helps us to appreciate the disaster that would happen to our planet if we were hit by a comet or asteroid.

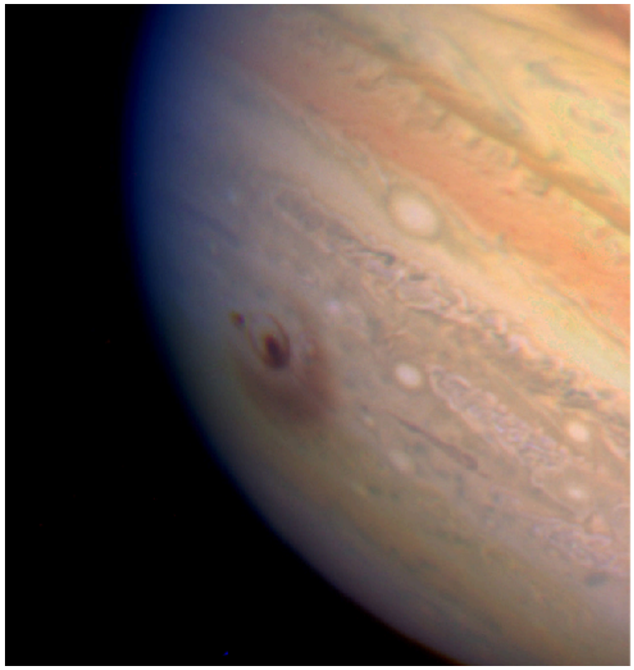


Figure 13.31 Impact Dust Cloud on Jupiter. These features result from the impact of Comet Shoemaker-Levy 9 with Jupiter, seen with the Hubble Space Telescope 105 minutes after the impact that produced the dark rings (the compact back dot came from another fragment). The inner edge of the diffuse, outer ring is about the same size as Earth. Later, the winds on Jupiter blended these features into a broad spot that remained visible for more than a month. (credit: modification of work by H. Hammel, MIT, and NASA/ESA)

For comets that do not meet so dramatic an end, measurements of the amount of gas and dust in their atmospheres permit us to estimate the total losses during one orbit. Typical loss rates are up to a million tons per day from an active comet near the Sun, adding up to some tens of millions of tons per orbit. At that rate, a typical comet will be gone after a few thousand orbits. This will probably be the fate of Comet Halley in the long run.

LINK TO LEARNING

This **History Channel video (https://openstaxcollege.org/l/30hischanUNIV)** shows a short discussion and animation from the TV documentary series *Universe*, showing the collision of Comet Shoemaker-Levy 9 with Jupiter.

CHAPTER 13 REVIEW

KEY TERMS

asteroid a stony or metallic object orbiting the Sun that is smaller than a major planet but that shows no evidence of an atmosphere or of other types of activity associated with comets

asteroid belt the region of the solar system between the orbits of Mars and Jupiter in which most asteroids are located; the main belt, where the orbits are generally the most stable, extends from 2.2 to 3.3 AU from the Sun

comet a small body of icy and dusty matter that revolves about the Sun; when a comet comes near the Sun, some of its material vaporizes, forming a large head of tenuous gas and often a tail

Kuiper belt a region of space beyond Neptune that is dynamically stable (like the asteroid belt); the source region for most short-period comets

near-Earth asteroid (NEA) an Earth-approaching asteroid, one whose orbit could bring it on a collision course with our planet

near-Earth object (NEO) a comet or asteroid whose path intersects the orbit of Earth

nucleus (of a comet) the solid chunk of ice and dust in the head of a comet

Oort cloud the large spherical region around the Sun from which most "new" comets come; a reservoir of objects with aphelia at about 50,000 AU

tail (of a comet) a tail consisting of two parts: the dust tail is made of dust loosened by the sublimation of ice in a comet that is then pushed by photons from the Sun into a curved stream; the ion tail is a stream of ionized particles evaporated from a comet and then swept away from the Sun by the solar wind

SUMMARY

13.1 Asteroids

The solar system includes many objects that are much smaller than the planets and their larger moons. The rocky ones are generally called asteroids. Ceres is the largest asteroid; about 15 are larger than 250 kilometers and about 100,000 are larger than 1 kilometer. Most are in the asteroid belt between Mars and Jupiter. The presence of asteroid families in the belt indicates that many asteroids are the remnants of ancient collisions and fragmentation. The asteroids include both primitive and differentiated objects. Most asteroids are classed as C-type, meaning they are composed of carbonaceous materials. Dominating the inner belt are S-type (stony) asteroids, with a few M-type (metallic) ones. We have spacecraft images of several asteroids and returned samples from asteroid Itokawa. Recent observations have detected a number of asteroid moons, making it possible to measure the masses and densities of the asteroids they orbit. The two largest asteroids, Ceres and Vesta, have been extensively studied from orbit by the *Dawn* spacecraft.

13.2 Asteroids and Planetary Defense

Near-Earth asteroids (NEAs), and near-Earth objects (NEOs) in general, are of interest in part because of their potential to hit Earth. They are on unstable orbits, and on timescales of 100 million years, they will either impact one of the terrestrial planets or the Sun, or be ejected. Most of them probably come from the asteroid belt, but some may be dead comets. NASA's Spaceguard Survey has found 90% of the NEAs larger than 1 kilometer, and none of the ones found so far are on a collision course with Earth. Scientists are actively working on possible technologies for planetary defense in case any NEOs are found on a collision course with Earth years in advance. For now, the most important task is to continue our surveys, so we can find the next Earth impactor before it finds us.

13.3 The "Long-Haired" Comets

Halley first showed that some comets are on closed orbits and return periodically to swing around the Sun. The heart of a comet is its nucleus, a few kilometers in diameter and composed of volatiles (primarily frozen H_2O) and solids (including both silicates and carbonaceous materials). Whipple first suggested this "dirty snowball" model in 1950; it has been confirmed by spacecraft studies of several comets. As the nucleus approaches the Sun, its volatiles evaporate (perhaps in localized jets or explosions) to form the comet's head or atmosphere, which escapes at about 1 kilometer per second. The atmosphere streams away from the Sun to form a long tail. The ESA Rosetta mission to Comet P67 (Churyumov-Gerasimenko) has greatly increased our knowledge of the nature of the nucleus and of the process by which comets release water and other volatiles when heated by sunlight.

13.4 The Origin and Fate of Comets and Related Objects

Oort proposed in 1950 that long-period comets are derived from what we now call the Oort cloud, which surrounds the Sun out to about 50,000 AU (near the limit of the Sun's gravitational sphere of influence) and contains between 10^{12} and 10^{13} comets. Comets also come from the Kuiper belt, a disk-shaped region beyond the orbit of Neptune, extending to 50 AU from the Sun. Comets are primitive bodies left over from the formation of the outer solar system. Once a comet is diverted into the inner solar system, it typically survives no more than a few thousand perihelion passages before losing all its volatiles. Some comets die spectacular deaths: Shoemaker-Levy 9, for example, broke into 20 pieces before colliding with Jupiter in 1994.

FOR FURTHER EXPLORATION

Articles

Asteroids

Asphang, E. "The Small Planets." *Scientific American* (May 2000): 46. On asteroids, including results from the NEAR mission.

Beatty, J. "The Falcon's Wild Flight." *Sky & Telescope* (September 2006): 34. On the Japanese mission to asteroid Itakawa.

Beatty, J. "NEAR Falls for Eros." *Sky & Telescope* (May 2001): 35. On the first landing on an asteroid.

Betz, E. "Dawn Mission Reveals Dwarf Planet Ceres." *Astronomy* (January 2016): 44. First images and discoveries.

Binzel, R. "A New Century for Asteroids." *Sky & Telescope* (July 2001): 44. Nice overview.

Boslaugh, M. "In Search of Death-Plunge Asteroids." *Astronomy* (July 2015): 28. On existing and proposed programs to search for Earth-crossing asteroids.

Cooke, B. "Fatal Attraction." *Astronomy* (May 2006): 46. On near-Earth asteroid Apophis, its orbit, and what we can learn from it.

Durda, D. "Odd Couples." *Astronomy* (December 2005): 54. On binary asteroids.

Durda, D. "All in the Family." *Astronomy* (February 1993): 36. Discusses asteroid families.

Oberg, J. "2013's Historic Russian Meteorite Fall" *Astronomy* (June 2012): 18. On the Chelyabinsk event.

Sheppard, S. “Dancing with the Planets.” *Sky & Telescope* (June 2016): 16. On Trojan asteroids that “follow” planets like Jupiter.

Talcott, R. “Galileo Views Gaspra.” *Astronomy* (February 1992): 52.

Yeomans, D. “Japan Visits an Asteroid.” *Astronomy* (March 2006): 32. On the *Hayabusa* probe exploration of asteroid Itakawa.

Zimmerman, R. “Ice Cream Sundaes and Mashed Potatoes.” *Astronomy* (February 1999): 54. On the NEAR mission.

Comets

Aguirre, E. “The Great Comet of 1997.” *Sky & Telescope* (July 1997): 50. On Comet Hale-Bopp.

Bakich, M. “How to Observe Comets.” *Astronomy* (December 2009): 50. A guide for amateur astronomers.

Gore, R. “Halley’s Comet ’86: Much More Than Met the Eye.” *National Geographic* (December 1986): 758. (Also, the March 1987 issue of *Sky & Telescope* was devoted to what we learned from Halley’s Comet in 1986.)

Hale, A. “Hale-Bopp Plus Ten.” *Astronomy* (July 2005): 76. The co-discoverer of a naked-eye comet tells the story of the discovery and what followed.

Jewett, D. “Mysterious Travelers: Comet Science.” *Sky & Telescope* (December. 2013): 18. Nice summary of what we know about comets and questions we have.

Rao, J. “How Often do Bright Comets Appear?” *Sky & Telescope* (November 2013): 30. Nice summary of bright comets in the last century and what factors make a comet spectacular in our skies.

Sekanina, Z. “Sungrazing Comets.” *Astronomy* (March 2006): 36.

Sheppard, S. “Beyond the Kuiper Belt.” *Sky & Telescope* (March 2015): 26. On Sedna and the Oort cloud.

Stern, S. “Evolution at the Edge.” *Astronomy* (September 2005): 46. How comet nuclei evolve with time.

Talcott, R. “Rendezvous with an Evolving Comet [Rosetta at Comet 67P/C-G].” *Astronomy* (September 2015): 44.

Tytell, D. “Deep Impact’s Hammer Throw.” *Sky & Telescope* (October 2006): 34. On the mission that threw a probe at the nucleus of a comet. See also (June 2005): 40.

Weissman, P. “A Comet Tale.” *Sky & Telescope* (February 2006): 36. A nice review of what we know and don’t know about the physical nature of comets.

Websites

Asteroids

Dawn Mission: **http://dawn.jpl.nasa.gov (http://dawn.jpl.nasa.gov)** . Discover more about this mission to the largest asteroids.

NEAR-Shoemaker Mission: **http://near.jhuapl.edu/ (http://near.jhuapl.edu/)** . Review background information and see great images from the mission that went by Mathilde and Eros.

Comets

Deep Impact Mission: **http://www.nasa.gov/mission_pages/deepimpact/main/ (http://www.nasa.gov/mission_pages/deepimpact/main/)** .

Kuiper Belt: **http://www2.ess.ucla.edu/~jewitt/kb.html (http://www2.ess.ucla.edu/~jewitt/kb.html)** . David Jewitt of the University of Hawaii keeps track of the objects that have been discovered.

Missions to Comets: **http://solarsystem.nasa.gov/missions/target/comets (http://solarsystem.nasa.gov/**

missions/target/comets) . Read about NASA's current and past missions to comets.

Stardust Mission: http://stardust.jpl.nasa.gov/home/index.html (http://stardust.jpl.nasa.gov/home/index.html) . Learn about this mission to collect a sample of a comet and bring it back to Earth.

Videos

Asteroids

Sweating the Small Stuff: The Fear and Fun of Near-Earth Asteroids: https://www.youtube.com/watch?v=5gyAvc5OhII (https://www.youtube.com/watch?v=5gyAvc5OhII) . Harvard Observatory Night Lecture by Jose-Luis Galache (1:18:07).

Unveiling Dwarf Planet Ceres: https://www.youtube.com/watch?v=_G9LudkLWOY (https://www.youtube.com/watch?v=_G9LudkLWOY) . A vonKarman Lecture by Dr. Carol Raymond, Oct. 2015, also includes Vesta results (1:18:38).

Comets

Great Comets, Comets in General, and Comet ISON: https://www.youtube.com/watch?v=DiBkYAnQ_C (https://www.youtube.com/watch?v=DiBkYAnQ_C) . Talk by Frank Summers, Space Telescope Science Institute (1:01:10).

Press Conference on the Impact of Comet Shoemaker-Levy 9 with Jupiter: https://www.youtube.com/watch?v=B-tUP8afEIo (https://www.youtube.com/watch?v=B-tUP8afEIo) . Day 2 after impact; July 17, 1994; with the discoverers and Heidi Hammel (1:22:29).

Rosetta: The Story So Far: https://www.ras.org.uk/events-and-meetings/public-lectures/public-lecture-videos/2726-rosetta-the-story-so-far (https://www.ras.org.uk/events-and-meetings/public-lectures/public-lecture-videos/2726-rosetta-the-story-so-far) . Royal Astronomical Society Lecture by Dr. Ian Wright (1:00:29).

COLLABORATIVE GROUP ACTIVITIES

A. Your group is a congressional committee charged with evaluating the funding for an effort to find all the NEAs (near-Earth asteroids) that are larger than 0.5 kilometers across. Make a list of reasons it would be useful to humanity to find such objects. What should we (could we) do if we found one that will hit Earth in a few years?

B. Many cultures considered comets bad omens. Legends associate comets with the deaths of kings, losses in war, or ends of dynasties. Did any members of your group ever hear about such folktales? Discuss reasons why comets in earlier times may have gotten this bad reputation.

C. Because asteroids have a variety of compositions and a low gravity that makes the removal of materials quite easy, some people have suggested that mining asteroids may be a way to get needed resources in the future. Make a list of materials in asteroids (and comets that come to the inner solar system) that may be valuable to a space-faring civilization. What are the pros and cons of undertaking mining operations on these small worlds?

D. As discussed in the feature box on **Comet Hunting as a Hobby**, amateur comet hunters typically spend more than 400 hours scanning the skies with their telescopes to find a comet. That's a lot of time to spend (usually alone, usually far from city lights, usually in the cold, and always in the dark). Discuss with members of your group whether you can see yourself being this dedicated. Why do people undertake such quests? Do you envy their dedication?

E. The largest Kuiper belt objects known are also called dwarf planets. All the planets (terrestrial, jovian, and dwarf) in our solar system have so far been named after mythological gods. (The dwarf planet names have moved away from Roman mythology to include the gods of other cultures.) Have your group discuss whether we should continue this naming tradition with newly discovered dwarf planets. Why or why not?

F. The total cost of the Rosetta mission to match courses with a comet was about 1.4 billion Euros (about $1.6 billion US). Have your group discuss whether this investment was worth it, giving reasons for whichever side you choose. (On the European Space Agency website, they put this cost in context by saying, “The figure is barely half the price of a modern submarine, or three Airbus 380 jumbo jets, and covers a period of almost 20 years, from the start of the project in 1996 through the end of the mission in 2015.”)

G. If an Earth-approaching asteroid were discovered early enough, humanity could take measures to prevent a collision. Discuss possible methods for deflecting or even destroying an asteroid or comet. Go beyond the few methods mentioned in the text and use your creativity. Give pros and cons for each method.

EXERCISES

Review Questions

1. Why are asteroids and comets important to our understanding of solar system history?

2. Give a brief description of the asteroid belt.

3. Describe the main differences between C-type and S-type asteroids.

4. In addition to the ones mentioned in **Exercise 13.3**, what is the third, rarer class of asteroids?

5. Vesta is unusual as it contains what mineral on its surface? What does the presence of this material indicate?

6. Compare asteroids of the asteroid belt with Earth-approaching asteroids. What is the main difference between the two groups?

7. Briefly describe NASA’s Spaceguard Survey. How many objects have been found in this survey?

8. Who first calculated the orbits of comets based on historical records dating back to antiquity?

9. Describe the nucleus of a typical comet and compare it with an asteroid of similar size.

10. Describe the two types of comet tails and how each are formed.

11. What classification is given to objects such as Pluto and Eris, which are large enough to be round, and whose orbits lie beyond that of Neptune?

12. Describe the origin and eventual fate of the comets we see from Earth.

13. What evidence do we have for the existence of the Kuiper belt? What kind of objects are found there?

14. Give brief descriptions of both the Kuiper belt and the Oort cloud.

Thought Questions

15. Give at least two reasons today's astronomers are so interested in the discovery of additional Earth-approaching asteroids.

16. Suppose you were designing a spacecraft that would match course with an asteroid and follow along its orbit. What sorts of instruments would you put on board to gather data, and what would you like to learn?

17. Suppose you were designing a spacecraft that would match course with a comet and move with it for a while. What sorts of instruments would you put on board to gather data, and what would you like to learn?

18. Suppose a comet were discovered approaching the Sun, one whose orbit would cause it to collide with Earth 20 months later, after perihelion passage. (This is approximately the situation described in the science-fiction novel *Lucifer's Hammer* by Larry Niven and Jerry Pournelle.) What could we do? Would there be any way to protect ourselves from a catastrophe?

19. We believe that chains of comet fragments like Comet Shoemaker-Levy 9's have collided not only with the jovian planets, but occasionally with their moons. What sort of features would you look for on the outer planet moons to find evidence of such collisions? (As an extra bonus, can you find any images of such features on a moon like Callisto? You can use an online site of planetary images, such as the *Planetary Photojournal*, at photojournal.jpl.nasa.gov.)

20. Why have we found so many objects in the Kuiper belt in the last two decades and not before then?

21. Why is it hard to give exact diameters for even the larger objects in the Kuiper belt?

Figuring For Yourself

22. Refer to **Example 13.1**. How would the calculation change if a typical comet in the Oort cloud is only 1 km in diameter?

23. Refer to **Example 13.1**. How would the calculation change if a typical comet in the Oort cloud is larger—say, 50 km in diameter?

24. The calculation in **Example 13.1** refers to the known Oort cloud, the source for most of the comets we see. If, as some astronomers suspect, there are 10 times this many cometary objects in the solar system, how does the total mass of cometary matter compare with the mass of Jupiter?

25. If the Oort cloud contains 10^{12} comets, and ten new comets are discovered coming close to the Sun each year, what percentage of the comets have been "used up" since the beginning of the solar system?

26. The mass of the asteroids is found mostly in the larger asteroids, so to estimate the total mass we need to consider only the larger objects. Suppose the three largest asteroids—Ceres (1000 km in diameter), Pallas (500 km in diameter), and Vesta (500 km in diameter)—account for half the total mass. Assume that each of these three asteroids has a density of 3 g/cm^3 and calculate their total mass. Multiply your result by 2 to obtain an estimate for the mass of the total asteroid belt. How does this compare with the mass of the Oort cloud?

27. Make a similar estimate for the mass of the Kuiper belt. The three largest objects are Pluto, Eris, and Makemake (each roughly 2000 km). In addition, assume there are eight objects (including Haumea, Orcus, Quaoar, Ixion, Varuna, and Charon, and objects that have not been named yet) with diameters of about 1000 km. Assume that all objects have Pluto's density of 2 g/cm^3. Calculate twice the mass of the largest 13 objects and compare it to the mass of the main asteroid belt.

28. What is the period of revolution about the Sun for an asteroid with a semi-major axis of 3 AU in the middle of the asteroid belt?

29. What is the period of revolution for a comet with aphelion at 5 AU and perihelion at the orbit of Earth?

14

COSMIC SAMPLES AND THE ORIGIN OF THE SOLAR SYSTEM

Figure 14.1 Planetesimals. This illustration depicts a disk of dust and gas around a new star. Material in this disk comes together to form planetesimals. (credit: modification of work by University of Copenhagen/Lars Buchhave, NASA)

Chapter Outline

Thinking Ahead

Imagine you are a scientist examining a sample of rock that had fallen from space a few days earlier and you find within it some of the chemical building blocks of life. How could you determine whether those “organic” materials came from space or were merely the result of earthly contamination?

We conclude our survey of the solar system with a discussion of its origin and evolution. Some of these ideas were introduced in **Other Worlds: An Introduction to the Solar System**; we now return to them, using the information we have learned about individual planets and smaller members of the solar system. In addition, astronomers have recently discovered several thousand planets around other stars, including numerous multiplanet systems. This is an important new source of data, providing us a perspective that extends beyond our own particular (and perhaps atypical) solar system.

But first, we want to look at another crucial way that astronomers learn about the ancient history of the solar system: by examining samples of *primitive matter*, the debris of the processes that formed the solar system some 4.5 billion years ago. Unlike the Apollo Moon rocks, these samples of cosmic material come to us free of charge—they literally fall from the sky. We call this material cosmic dust and meteorites.

14.1 METEORS

Learning Objectives

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

- Explain what a meteor is and why it is visible in the night sky
- Describe the origins of meteor showers

As we saw in **Comets and Asteroids: Debris of the Solar System**, the ices in comets evaporate when they get close to the Sun, together spraying millions of tons of rock and dust into the inner solar system. There is also dust from asteroids that have collided and broken up. Earth is surrounded by this material. As each of the larger dust or rock particles enters Earth's atmosphere, it creates a brief fiery trail; this is often called a *shooting star*, but it is properly known as a **meteor**.

Observing Meteors

Meteors are tiny solid particles that enter Earth's atmosphere from interplanetary space. Since the particles move at speeds of many kilometers per second, friction with the air vaporizes them at altitudes between 80 and 130 kilometers. The resulting flashes of light fade out within a few seconds. These "shooting stars" got their name because at night their luminous vapors look like stars moving rapidly across the sky. To be visible, a meteor must be within about 200 kilometers of the observer. On a typical dark, moonless night, an alert observer can see half a dozen meteors per hour. These *sporadic meteors*—those not associated with a meteor shower (explained in the next section)—are random occurrences. Over the entire Earth, the total number of meteors bright enough to be visible totals about 25 million per day.

The typical meteor is produced by a particle with a mass of less than 1 gram—no larger than a pea. How can we see such a small particle? The light you see comes from the much larger region of heated, glowing gas surrounding this little grain of interplanetary material. Because of its high speed, the energy in a pea-sized meteor is as great as that of an artillery shell fired on Earth, but this energy is dispersed high in Earth's atmosphere. (When these tiny projectiles hit an airless body like the Moon, they do make small craters and generally pulverize the surface.)

If a particle the size of a golf ball strikes our atmosphere, it produces a much brighter trail called a fireball (**Figure 14.2**). A piece as large as a bowling ball has a fair chance of surviving its fiery entry if its approach speed is not too high. The total mass of meteoric material entering Earth's atmosphere is estimated to be about 100 tons per day (which seems like a lot if you imagine it all falling in one place, but remember it is spread out all over our planet's surface).

Figure 14.2 Fireball. When a larger piece of cosmic material strikes Earth's atmosphere, it can make a bright fireball. This time-lapse meteor image was captured in April 2014 at the Atacama Large Millimeter/Submillimeter Array (ALMA). The visible trail results from the burning gas around the particle. (credit: modification of work by ESO/C Malin)

LINK TO LEARNING

While it is difficult to capture images of fireballs and other meteors with still photography, it's easy to capture the movement of these objects on video. The American Meteor Society maintains a **website (https://openstaxcollege.org/l/30ammetsocweb)** on which their members can share such videos.

Meteor Showers

Many—perhaps most—of the meteors that strike Earth are associated with specific comets. Some of these periodic comets still return to our view; others have long ago fallen apart, leaving only a trail of dust behind them. The dust particles from a given comet retain approximately the orbit of their parent, continuing to move together through space but spreading out over the orbit with time. When Earth, in its travels around the Sun, crosses such a dust stream, we see a sudden burst of meteor activity that usually lasts several hours; such an event is called a **meteor shower**.

The dust particles and pebbles that produce meteor showers are moving together in space before they encounter Earth. Thus, as we look up at the atmosphere, their parallel paths seem to come toward us from a place in the sky called the *radiant*. This is the direction in space from which the meteor stream seems to be diverging, just as long railroad tracks seem to diverge from a single spot on the horizon (**Figure 14.3**). Meteor showers are often designated by the constellation in which this radiant is located: for example, the Perseid meteor shower has its radiant in the constellation of Perseus. But you are likely to see shower meteors anywhere in the sky, not just in the constellation of the radiant. The characteristics of some of the more famous meteor showers are summarized in **Table 14.1**.

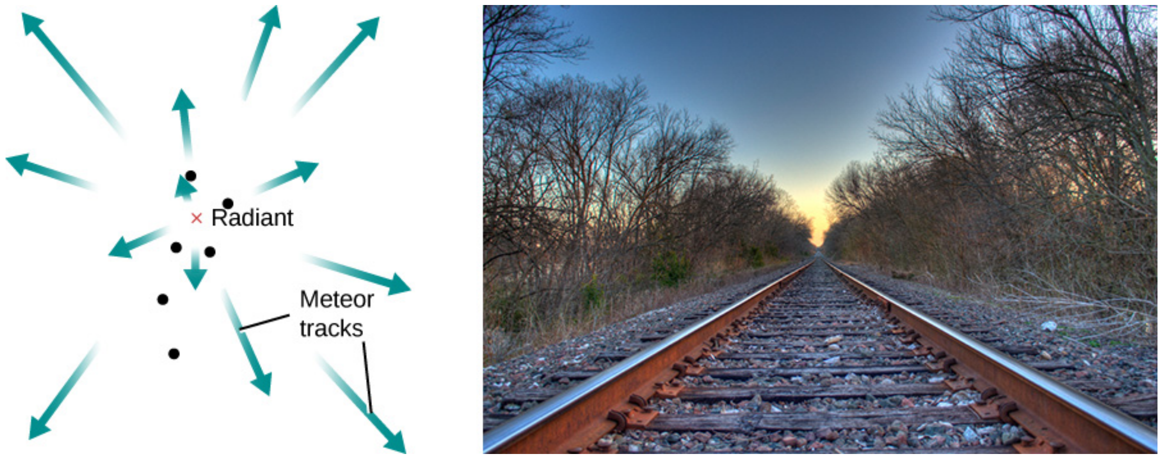


Figure 14.3 Radiant of a Meteor Shower. The tracks of the meteors diverge from a point in the distance, just as long, parallel railroad tracks appear to do. (credit "tracks": Nathan Vaughn)

Major Annual Meteor Showers

Shower Name	Date of Maximum	Associated Parent Object	Comet's Period (years)
Quadrantid	January 3–4	2003EH (asteroid)	—
Lyrid	April 22	Comet Thatcher	415
Eta Aquarid	May 4–5	Comet Halley	76
Delta Aquarid	July 29–30	Comet Machholz	—
Perseid	August 11–12	Comet Swift-Tuttle	133
Orionid	October 20–21	Comet Halley	76
Southern Taurid	October 31	Comet Encke	3
Leonid	November 16–17	Comet Tempel-Tuttle	33
Geminid	December 13	Phaethon (asteroid)	1.4

Table 14.1

The meteoric dust is not always evenly distributed along the orbit of the comet, so during some years more meteors are seen when Earth intersects the dust stream, and in other years fewer. For example, a very clumpy distribution is associated with the Leonid meteors, which in 1833 and again in 1866 (after an interval of 33 years—the period of the comet) yielded the most spectacular showers (sometimes called *meteor storms*) ever recorded (Figure 14.4). During the Leonid storm on November 17, 1866, up to a hundred meteors were observed per second in some locations. The Leonid shower of 2001 was not this intense, but it peaked at nearly a thousand meteors per hour—one every few seconds—observable from any dark viewing site.

Figure 14.4 Leonid Meteor Storm. A painting depicts the great meteor shower or storm of 1833, shown with a bit of artistic license.

The most dependable annual meteor display is the Perseid shower, which appears each year for about three nights near August 11. In the absence of bright moonlight, you can see one meteor every few minutes during a typical Perseid shower. Astronomers estimate that the total combined mass of the particles in the Perseid swarm is nearly a billion tons; the comet that gave rise to the particles in that swarm, called Swift-Tuttle, must originally have had at least that much mass. However, if its initial mass were comparable to the mass measured for Comet Halley, then Swift-Tuttle would have contained several hundred billion tons, suggesting that only a very small fraction of the original cometary material survives in the meteor stream.

LINK TO LEARNING

The California Academy of Sciences has a short animated **guide (https://openstaxcollege.org/l/30howobsmetsho)** on "How to Observe a Meteor Shower."

No shower meteor has ever survived its flight through the atmosphere and been recovered for laboratory analysis. However, there are other ways to investigate the nature of these particles and thereby gain additional insight into the comets from which they are derived. Analysis of the flight paths of meteors shows that most of them are very light or porous, with densities typically less than 1.0 g/cm^3. If you placed a fist-sized lump of meteor material on a table in Earth's gravity, it might well fall apart under its own weight.

Such light particles break up very easily in the atmosphere, accounting for the failure of even relatively large shower meteors to reach the ground. Comet dust is apparently fluffy, rather inconsequential stuff. NASA's Stardust mission used a special substance, called aerogel, to collect these particles. We can also infer this from the tiny comet particles recovered in Earth's atmosphere with high-flying aircraft (see **Figure 13.19**). This fluff, by its very nature, cannot reach Earth's surface intact. However, more substantial fragments from asteroids do make it into our laboratories, as we will see in the next section.

SEEING FOR YOURSELF

Showering with the Stars

Observing a meteor shower is one of the easiest and most enjoyable astronomy activities for beginners (Figure 14.5). The best thing about it is that you don't need a telescope or binoculars—in fact, they would positively get in your way. What you do need is a site far from city lights, with an unobstructed view of as much sky as possible. While the short bright lines in the sky made by individual meteors could, in theory, be traced back to a radiant point (as shown in Figure 14.3), the quick blips of light that represent the end of the meteor could happen anywhere above you.

Figure 14.5 Perseid Meteor Shower. This twenty-second exposure shows a meteor during the 2015 Perseid meteor shower. (credit: NASA/Bill Ingalls)

The key to observing meteor showers is not to restrict your field of view, but to lie back and scan the sky alertly. Try to select a good shower (see the list in Table 14.1) and a night when the Moon will not be bright at the time you are observing. The Moon, street lights, vehicle headlights, bright flashlights, and cell phone and tablet screens will all get in the way of your seeing the faint meteor streaks.

You will see more meteors after midnight, when you are on the hemisphere of Earth that faces forward—in the direction of Earth's revolution around the Sun. Before midnight, you are observing from the "back side" of Earth, and the only meteors you see will be those that traveled fast enough to catch up with Earth's orbital motion.

When you've gotten away from all the lights, give your eyes about 15 minutes to get "dark adapted"—that is, for the pupils of your eyes to open up as much as possible. (This adaptation is the same thing that happens in a dark movie theater. When you first enter, you can't see a thing, but eventually, as your pupils open wider, you can see pretty clearly by the faint light of the screen—and notice all that spilled popcorn on the floor.)

Seasoned meteor observers find a hill or open field and make sure to bring warm clothing, a blanket, and a thermos of hot coffee or chocolate with them. (It’s also nice to take along someone with whom you enjoy sitting in the dark.) Don’t expect to see fireworks or a laser show: meteor showers are subtle phenomena, best approached with a patience that reflects the fact that some of the dust you are watching burn up may first have been gathered into its parent comet more than 4.5 billion years ago, as the solar system was just forming.

14.2 METEORITES: STONES FROM HEAVEN

Learning Objectives

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

- Explain the origin of meteorites and the difference between a meteor and a meteorite
- Describe how most meteorites have been found
- Explain how primitive stone meteorites are significantly different from other types
- Explain how the study of meteorites informs our understanding of the age of the solar system.

Any fragment of interplanetary debris that survives its fiery plunge through Earth’s atmosphere is called a **meteorite**. Meteorites fall only very rarely in any one locality, but over the entire Earth thousands fall each year. Some meteorites are loners, but many are fragments from the breakup in the atmosphere of a single larger object. These rocks from the sky carry a remarkable record of the formation and early history of the solar system.

Extraterrestrial Origin of Meteorites

Occasional meteorites have been found throughout history, but their extraterrestrial origin was not accepted by scientists until the beginning of the nineteenth century. Before that, these strange stones were either ignored or considered to have a supernatural origin.

The falls of the earliest recovered meteorites are lost in the fog of mythology. A number of religious texts speak of stones from heaven, which sometimes arrived at opportune moments to smite the enemies of the authors of those texts. At least one sacred meteorite has apparently survived in the form of the Ka’aba, the holy black stone in Mecca that is revered by Islam as a relic from the time of the Patriarchs—although understandably, no chip from this sacred stone has been subject to detailed chemical analysis.

The modern scientific history of the meteorites begins in the late eighteenth century, when a few scientists suggested that some strange-looking stones had such peculiar composition and structure that they were probably not of terrestrial origin. The idea that indeed “stones fall from the sky” was generally accepted only after a scientific team led by French physicist Jean-Baptiste Biot investigated a well-observed fall in 1803.

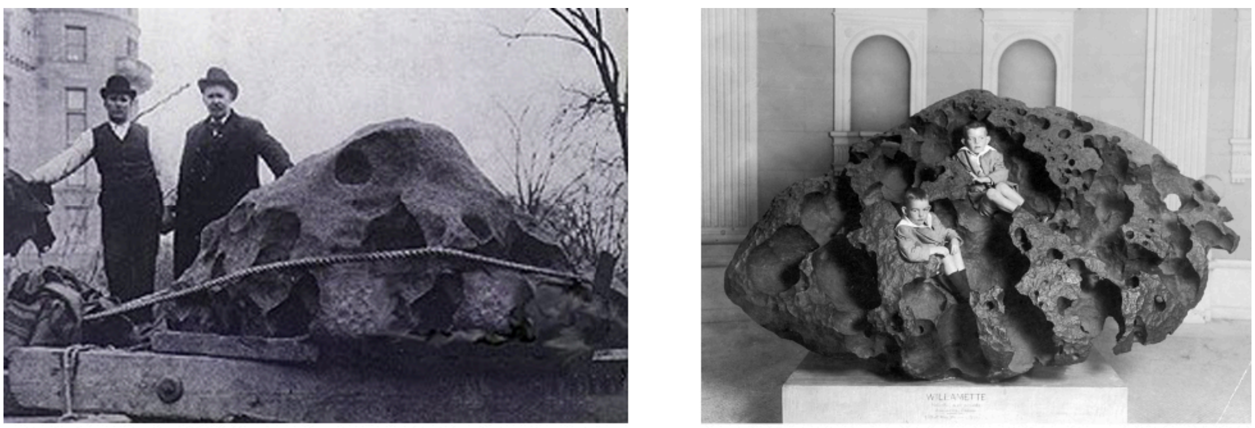
Meteorites sometimes fall in groups or showers. Such a fall occurs when a single larger object breaks up during its violent passage through the atmosphere. It is important to remember that such a *shower of meteorites* has nothing to do with a *meteor shower*. No meteorites have ever been recovered in association with meteor showers. Whatever the ultimate source of the meteorites, they do not appear to come from the comets or their associated particle streams.

Meteorite Falls and Finds

Meteorites are found in two ways. First, sometimes bright meteors (fireballs) are observed to penetrate the atmosphere to low altitudes. If we search the area beneath the point where the fireball burned out, we may find one or more remnants that reached the ground. Observed *meteorite falls*, in other words, may lead to the recovery of fallen meteorites. (A few meteorites have even hit buildings or, very rarely, people; see **Making Connections: Some Striking Meteorites**). The 2013 Chelyabinsk fireball, which we discussed in the chapter on **Comets and Asteroids: Debris of the Solar System**, produced tens of thousands of small meteorites, many of them easy to find because these dark stones fell on snow.

There are, however, many false alarms about meteorite falls. Most observers of a bright fireball conclude that part of it hit the ground, but that is rarely the case. Every few months news outlets report that a meteorite has been implicated in the start of a fire. Such stories have always proved to be wrong. The meteorite is ice-cold in space, and most of its interior remains cold even after its brief fiery plunge through the atmosphere. A freshly fallen meteorite is more likely to acquire a coating of frost than to start a fire.

People sometimes discover unusual-looking rocks that turn out to be meteoritic; these rocks are termed *meteorite finds*. Now that the public has become meteorite-conscious, many unusual fragments, not all of which turn out to be from space, are sent to experts each year. Some scientists divide these objects into two categories: “meteorites” and “meteorwrongs.” Outside Antarctica (see the next paragraph), genuine meteorites turn up at an average rate of 25 or so per year. Most of these end up in natural history museums or specialized meteoritical laboratories throughout the world (**Figure 14.6**).



(a) (b)

Figure 14.6 Meteorite Find. (a) This early twentieth century photo shows a 15-ton iron meteorite found in the Willamette Valley in Oregon. Although known to Native Americans in the area, it was “discovered” by an enterprising local farmer in 1902, who proceeded to steal it and put it on display. (b) It was eventually purchased for the American Museum of Natural History and is now on display in the museum’s Rose Center in New York City as the largest iron meteorite in the United States. In this 1911 photo, two young boys are perched in the meteor’s crevices.

Since the 1980s, sources in the Antarctic have dramatically increased our knowledge of meteorites. More than ten thousand meteorites have been recovered from the Antarctic as a result of the motion of the ice in some parts of that continent (**Figure 14.7**). Meteorites that fall in regions where ice accumulates are buried and then carried slowly to other areas where the ice is gradually worn away. After thousands of years, the rock again finds itself on the surface, along with other meteorites carried to these same locations. The ice thus concentrates the meteorites that have fallen both over a large area and over a long period of time. Once on the surface, the rocks stand out in contrast to the ice and are thus easier to spot than in other places on our rocky planet.

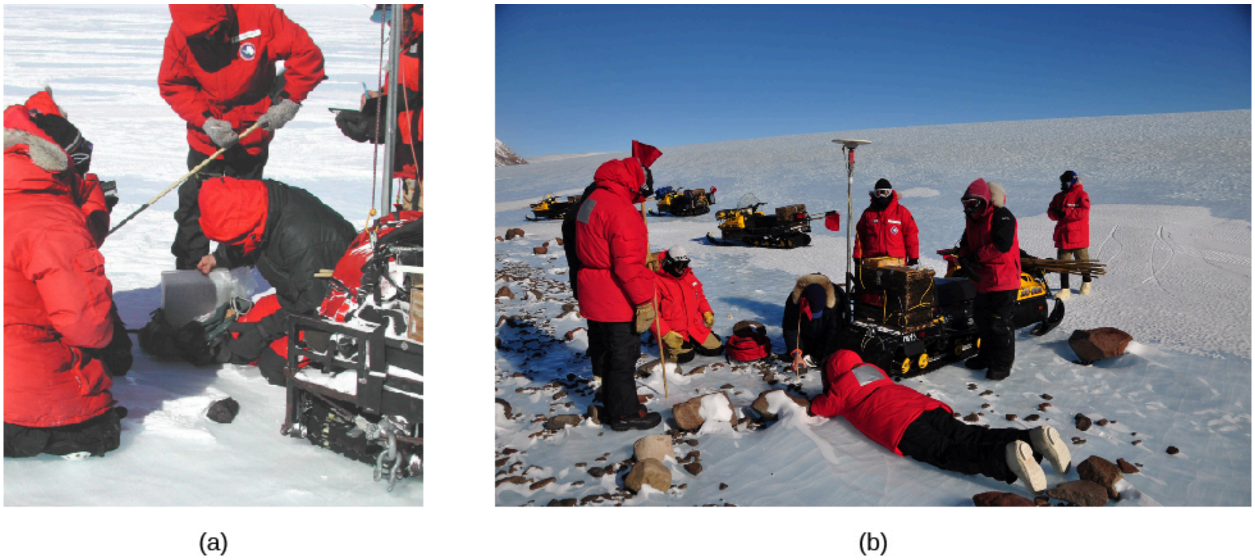


Figure 14.7 Antarctic Meteorite. (a) The US Antarctic Search for Meteorites (ANSMET) team recovers a meteorite from the Antarctic ice during a 2001–2002 mission. (b) The team is shown with some of the equipment used in the search. (credit a, b: modification of work by NASA)

MAKING CONNECTIONS

Some Striking Meteorites

Although meteorites fall regularly onto Earth's surface, few of them have much of an impact on human civilization. There is so much water and uninhabited land on our planet that rocks from space typically fall where no one even sees them come down. But given the number of meteorites that land each year, you may not be surprised that a few have struck buildings, cars, and even people. In September 1938, for example, a meteorite plunged through the roof of Edward McCain's garage, where it became embedded in the seat of his Pontiac Coupe (**Figure 14.8**).

In November 1982, Robert and Wanda Donahue of Wethersfield, Connecticut, were watching *M*A*S*H** on television when a 6-pound meteorite came thundering through their roof, making a hole in the living room ceiling. After bouncing, it finally came to rest under their dining room table.

Eighteen-year-old Michelle Knapp of Peekskill, New York, got quite a surprise one morning in October 1992. She had just purchased her very first car, her grandmother's 1980 Chevy Malibu. But she awoke to find its rear end mangled and a crater in the family driveway—thanks to a 3-pound meteorite. Michelle was not sure whether to be devastated by the loss of her car or thrilled by all the media attention.

In June 1994, Jose Martin and his wife were driving from Madrid, Spain, to a golfing vacation when a fist-sized meteorite crashed through the windshield of their car, bounced off the dashboard, broke Jose's little finger, and then landed in the back seat. Before Martin, the most recent person known to have been struck by a meteorite was Annie Hodges of Sylacauga, Alabama. In November 1954, she was napping on a couch when a meteorite came through the roof, bounced off a large radio set, and hit her first on the arm and then on the leg.

The fireball that exploded at an altitude of about 20 kilometers near the Russian city of Chelyabinsk on February 15, 2013, produced a very large meteorite shower, and quite a few of the small rocks hit buildings. None is known to have hit people, however, and the individual meteorites were so small that they did not do much damage—much less than the shockwave from the exploding fireball, which broke the glass in thousands of windows.

Figure 14.8 Benld Meteorite. A meteorite (inset) left a hole in the seat cushion of Edward McCain’s car. (credit: “Shsilver”/Wikimedia Commons)

Meteorite Classification

The meteorites in our collections have a wide range of compositions and histories, but traditionally they have been placed into three broad classes. First are the **irons**, composed of nearly pure metallic nickel-iron. Second are the **stones**, the term used for any silicate or rocky meteorite. Third are the rarer **stony-irons**, made (as the name implies) of mixtures of stone and metallic iron (Figure 14.9).

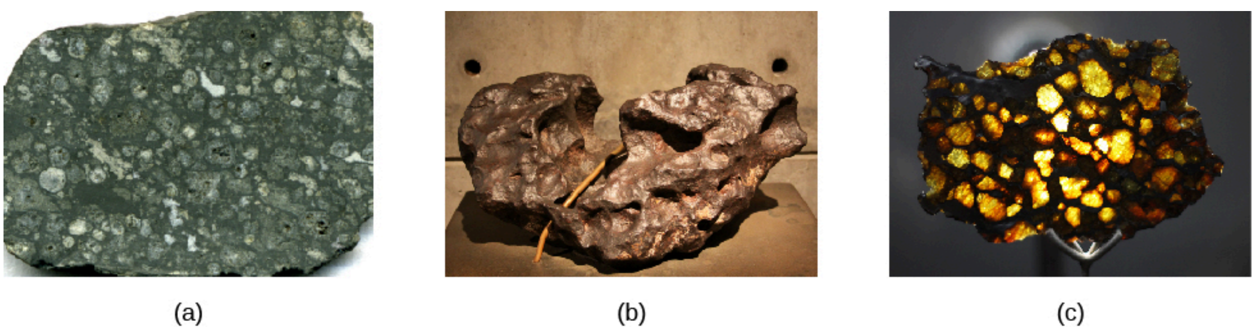


Figure 14.9 Meteorite Types. (a) This piece of the Allende carbonaceous meteorite has white inclusions that may date back to before the formation of the solar nebula. (b) This fragment is from the iron meteorite responsible for the formation of Meteor Crater in Arizona. (c) This piece of the Imilac stony-iron meteorite is a beautiful mixture of green olivine crystals and metallic iron. (credit a: modification of work by James St. John; credit b: modification of work by “Taty2007”/Wikimedia Commons; credit c: modification of work by Juan Manuel Fluxà)

Of these three types, the irons and stony-irons are the most obviously extraterrestrial because of their metallic content. Pure iron almost never occurs naturally on Earth; it is generally found here as an oxide (chemically combined with oxygen) or other mineral ore. Therefore, if you ever come across a chunk of metallic iron, it is sure to be either man-made or a meteorite.

The stones are much more common than the irons but more difficult to recognize. Often laboratory analysis is required to demonstrate that a particular sample is really of extraterrestrial origin, especially if it has lain on the ground for some time and been subject to weathering. The most scientifically valuable stones are those collected immediately after they fall, or the Antarctic samples preserved in a nearly pristine state by ice.

Table 14.2 summarizes the frequencies of occurrence of the different classes of meteorites among the fall, find, and Antarctic categories.

Frequency of Occurrence of Meteorite Classes

Class	Falls (%)	Finds (%)	Antarctic (%)
Primitive stones	88	51	85
Differentiated stones	8	2	12
Irons	3	42	2
Stony-irons	1	5	1

Table 14.2

Ages and Compositions of Meteorites

It was not until the ages of meteorites were measured and their compositions analyzed in detail that scientists appreciated their true significance. The meteorites include the oldest and most primitive materials available for direct study in the laboratory. The ages of stony meteorites can be determined from the careful measurement of radioactive isotopes and their decay products. Almost all meteorites have radioactive ages between 4.50 and 4.56 billion years, as old as any ages we have measured in the solar system. The few younger exceptions are igneous rocks that have been ejected from cratering events on the Moon or Mars (and have made their way to Earth).

The average age for the most primitive meteorites, calculated using the most accurate values now available for radioactive half-lives, is 4.56 billion years, with an uncertainty of less than 0.01 billion years. This value (which we round off to 4.5 billion years in this book) is taken to represent the *age of the solar system*—the time since the first solids condensed and began to form into larger bodies.

The traditional classification of meteorites into irons, stones, and stony-irons is easy to use because it is obvious from inspection which category a meteorite falls into (although it may be much more difficult to distinguish a meteoritic stone from a terrestrial rock). More scientifically significant, however, is the distinction between *primitive* and *differentiated* meteorites. The differentiated meteorites are fragments of larger parent bodies that were molten before they broke up, allowing the denser materials (such as metals) to sink to their centers. Like many rocks on Earth, they have been subject to a degree of chemical reshuffling, with the different materials sorted according to density. Differentiated meteorites include the irons, which come from the metal cores of their parent bodies; stony-irons, which probably originate in regions between a metal core and a stony mantle; and some stones that are composed of mantle or crust material from the their differentiated parent bodies.

The Most Primitive Meteorites

For information on the *earliest* history of the solar system, we turn to the primitive meteorites—those made of materials that have *not* been subject to great heat or pressure since their formation. We can look at the spectrum of sunlight reflected from asteroids and compare their compositions with those of primitive meteorites. Such analysis indicates that their parent bodies are almost certainly asteroids. Since asteroids are believed to be fragments left over from the formation process of the solar system, it makes sense that they should be the parent bodies of the primitive meteorites.

The great majority of the meteorites that reach Earth are primitive stones. Many of them are composed of light-colored gray silicates with some metallic grains mixed in, but there is also an important group of darker stones called *carbonaceous meteorites*. As their name suggests, these meteorites contain carbon, but we also find various complex organic molecules in them—chemicals based on carbon, which on Earth are the chemical building blocks of life. In addition, some of them contain chemically bound water, and many are depleted in metallic iron. The carbonaceous (or C-type) asteroids are concentrated in the outer part of the asteroid belt.

Among the most useful of these meteorites have been the Allende meteorite that fell in Mexico (see **Figure 14.9**), the Murchison meteorite that fell in Australia (both in 1969), and the Tagish Lake meteorite that landed in a winter snowdrift on Tagish Lake, Canada, in 2000. (The fragile bits of dark material from the Tagish Lake meteorite were readily visible against the white snow, although at first they were mistaken for wolf droppings.)

The Murchison meteorite (**Figure 14.10**) is known for the variety of organic chemicals it has yielded. Most of the carbon compounds in carbonaceous meteorites are complex, tarlike substances that defy exact analysis. Murchison also contains 16 amino acids (the building blocks of proteins), 11 of which are rare on Earth. The most remarkable thing about these organic molecules is that they include equal numbers with right-handed and left-handed molecular symmetry. Amino acids can have either kind of symmetry, but all life on Earth has evolved using only the *left-handed* versions to make proteins. The presence of both kinds of amino acids clearly demonstrates that the ones in the meteorites had an extraterrestrial origin.

Figure 14.10 Murchison Meteorite. A fragment of the meteorite that fell near the small town of Murchison, Australia, is shown next to a small sample of its material in a test tube, used for analysis of its chemical makeup.

These naturally occurring amino acids and other complex organic molecules in Murchison—formed without the benefit of the sheltering environment of planet Earth—show that a great deal of interesting chemistry must have taken place when the solar system was forming. If so, then perhaps some of the molecular building blocks of life on Earth were first delivered by primitive meteorites and comets. This is an interesting idea because our planet was probably much too hot for any organic materials to survive its earliest history. But after Earth's surface cooled, the asteroid and comet fragments that pelted it could have refreshed its supply of organic materials.

14.3 FORMATION OF THE SOLAR SYSTEM

Learning Objectives

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

- Describe the motion, chemical, and age constraints that must be met by any theory of solar system formation
- Summarize the physical and chemical changes during the solar nebula stage of solar system formation
- Explain the formation process of the terrestrial and giant planets
- Describe the main events of the further evolution of the solar system

As we have seen, the comets, asteroids, and meteorites are surviving remnants from the processes that formed the solar system. The planets, moons, and the Sun, of course, also are the products of the formation process, although the material in them has undergone a wide range of changes. We are now ready to put together the information from all these objects to discuss what is known about the origin of the solar system.

Observational Constraints

There are certain basic properties of the planetary system that any theory of its formation must explain. These may be summarized under three categories: motion constraints, chemical constraints, and age constraints. We call them *constraints* because they place restrictions on our theories; unless a theory can explain the observed facts, it will not survive in the competitive marketplace of ideas that characterizes the endeavor of science. Let's take a look at these constraints one by one.

There are many regularities to the motions in the solar system. We saw that the planets all revolve around the Sun in the same direction and approximately in the plane of the Sun's own rotation. In addition, most of the planets rotate in the same direction as they revolve, and most of the moons also move in counterclockwise orbits (when seen from the north). With the exception of the comets and other trans-neptunian objects, the motions of the system members define a disk or Frisbee shape. Nevertheless, a full theory must also be prepared to deal with the exceptions to these trends, such as the *retrograde rotation* (not revolution) of Venus.

In the realm of chemistry, we saw that Jupiter and Saturn have approximately the same composition—dominated by hydrogen and helium. These are the two largest planets, with sufficient gravity to hold on to any gas present when and where they formed; thus, we might expect them to be representative of the original material out of which the solar system formed. Each of the other members of the planetary system is, to some degree, lacking in the light elements. A careful examination of the composition of solid solar-system objects shows a striking progression from the metal-rich inner planets, through those made predominantly of rocky materials, out to objects with ice-dominated compositions in the outer solar system. The comets in the Oort cloud and the trans-neptunian objects in the Kuiper belt are also icy objects, whereas the asteroids represent a transitional rocky composition with abundant dark, carbon-rich material.

As we saw in **Other Worlds: An Introduction to the Solar System**, this general chemical pattern can be interpreted as a temperature sequence: hot near the Sun and cooler as we move outward. The inner parts of the system are generally missing those materials that could not condense (form a solid) at the high temperatures found near the Sun. However, there are (again) important exceptions to the general pattern. For example, it is difficult to explain the presence of water on Earth and Mars if these planets formed in a region where the temperature was too hot for ice to condense, unless the ice or water was brought in later from cooler regions. The extreme example is the observation that there are polar deposits of ice on both Mercury and the Moon; these are almost certainly formed and maintained by occasional comet impacts.

As far as age is concerned, we discussed that radioactive dating demonstrates that some rocks on the surface of Earth have been present for at least 3.8 billion years, and that certain lunar samples are 4.4 billion years old. The primitive meteorites all have radioactive ages near 4.5 billion years. The age of these unaltered building blocks is considered the age of the planetary system. The similarity of the measured ages tells us that planets formed and their crusts cooled within a few tens of millions of years (at most) of the beginning of the solar system.

Further, detailed examination of primitive meteorites indicates that they are made primarily from material that condensed or coagulated out of a hot gas; few identifiable fragments appear to have survived from before this hot-vapor stage 4.5 billion years ago.

The Solar Nebula

All the foregoing constraints are consistent with the general idea, introduced in **Other Worlds: An Introduction to the Solar System**, that the solar system formed 4.5 billion years ago out of a rotating cloud of vapor and dust—which we call the solar nebula—with an initial composition similar to that of the Sun today. As the solar nebula collapsed under its own gravity, material fell toward the center, where things became more and more concentrated and hot. Increasing temperatures in the shrinking nebula vaporized most of the solid material that was originally present.

At the same time, the collapsing nebula began to rotate faster through the conservation of angular momentum (see the **Orbits and Gravity** and **Earth, Moon, and Sky** chapters). Like a figure skater pulling her arms in to spin faster, the shrinking cloud spun more quickly as time went on. Now, think about how a round object spins. Close to the poles, the spin rate is slow, and it gets faster as you get closer to the equator. In the same way, near the poles of the nebula, where orbits were slow, the nebular material fell directly into the center. Faster moving material, on the other hand, collapsed into a flat disk revolving around the central object (**Figure 14.11**). The existence of this disk-shaped rotating nebula explains the primary motions in the solar system that we discussed in the previous section. And since they formed from a rotating disk, the planets all orbit the same way.

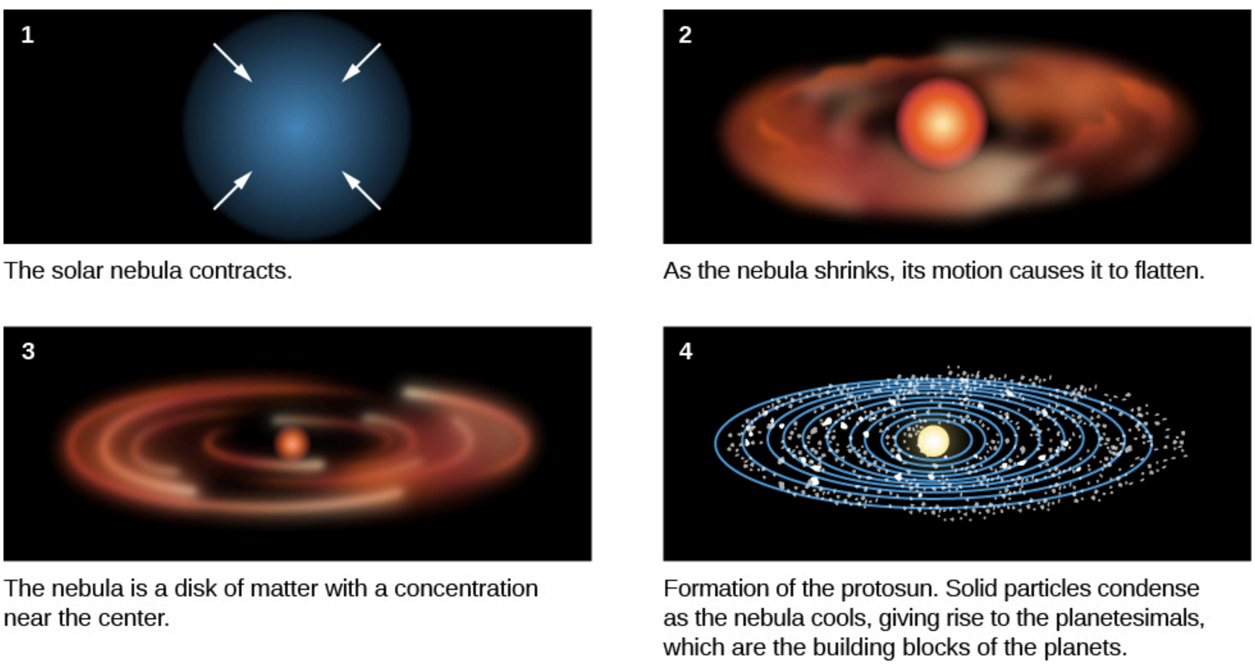


Figure 14.11 Steps in Forming the Solar System. This illustration shows the steps in the formation of the solar system from the solar nebula. As the nebula shrinks, its rotation causes it to flatten into a disk. Much of the material is concentrated in the hot center, which will ultimately become a star. Away from the center, solid particles can condense as the nebula cools, giving rise to planetesimals, the building blocks of the planets and moons.

Picture the solar nebula at the end of the collapse phase, when it was at its hottest. With no more gravitational energy (from material falling in) to heat it, most of the nebula began to cool. The material in the center, however, where it was hottest and most crowded, formed a *star* that maintained high temperatures in its immediate neighborhood by producing its own energy. Turbulent motions and magnetic fields within the disk can drain away angular momentum, robbing the disk material of some of its spin. This allowed some material to continue to fall into the growing star, while the rest of the disk gradually stabilized.

The temperature within the disk decreased with increasing distance from the Sun, much as the planets' temperatures vary with position today. As the disk cooled, the gases interacted chemically to produce compounds; eventually these compounds condensed into liquid droplets or solid grains. This is similar to the process by which raindrops on Earth condense from moist air as it rises over a mountain.

Let's look in more detail at how material condensed at different places in the maturing disk (**Figure 14.12**). The first materials to form solid grains were the metals and various rock-forming silicates. As the temperature dropped, these were joined throughout much of the solar nebula by sulfur compounds and by carbon- and water-rich silicates, such as those now found abundantly among the asteroids. However, in the inner parts of the disk, the temperature never dropped low enough for such materials as ice or carbonaceous organic compounds to condense, so they were lacking on the innermost planets.

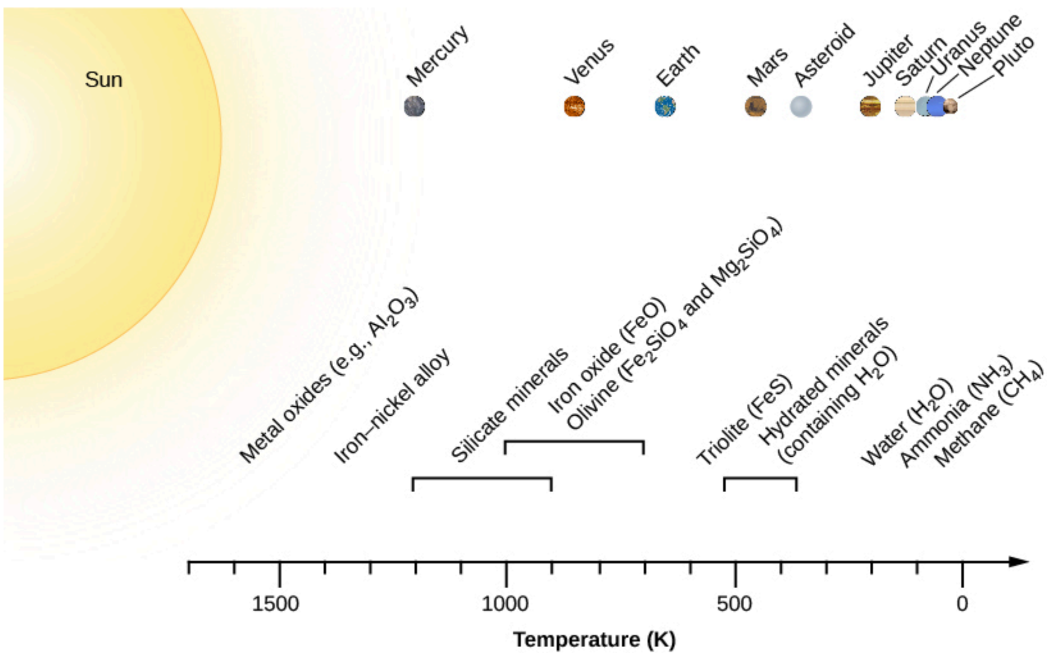


Figure 14.12 Chemical Condensation Sequence in the Solar Nebula. The scale along the bottom shows temperature; above are the materials that would condense out at each temperature under the conditions expected to prevail in the nebula.

Far from the Sun, cooler temperatures allowed the oxygen to combine with hydrogen and condense in the form of water (H_2O) ice. Beyond the orbit of Saturn, carbon and nitrogen combined with hydrogen to make ices such as methane (CH_4) and ammonia (NH_3). This sequence of events explains the basic chemical composition differences among various regions of the solar system.

EXAMPLE 14.1

Rotation of the Solar Nebula

We can use the concept of angular momentum to trace the evolution of the collapsing solar nebula. The angular momentum of an object is proportional to the square of its size (diameter) times its period of rotation (D^2/P). If angular momentum is conserved, then any change in the size of a nebula must be compensated for by a proportional change in period, in order to keep D^2/P constant. Suppose the solar nebula began with a diameter of 10,000 AU and a rotation period of 1 million years. What is its rotation period when it has shrunk to the size of Pluto's orbit, which **Appendix F** tells us has a radius of about 40 AU?

Solution

We are given that the final diameter of the solar nebula is about 80 AU. Noting the initial state before the collapse and the final state at Pluto's orbit, then

$$\frac{P_{\text{fina}}}{P_{\text{initial}}} = \left(\frac{D_{\text{fina}}}{D_{\text{initial}}}\right)^2 = \left(\frac{80}{10{,}000}\right)^2 = (0.008)^2 = 0.000064$$

With P_{initial} equal to 1,000,000 years, P_{final}, the new rotation period, is 64 years. This is a lot shorter than the actual time Pluto takes to go around the Sun, but it gives you a sense of the kind of speeding up the conservation of angular momentum can produce. As we noted earlier, other mechanisms helped the material in the disk lose angular momentum before the planets fully formed.

Check Your Learning

What would the rotation period of the nebula in our example be when it had shrunk to the size of Jupiter's orbit?

Answer:

The period of the rotating nebula is inversely proportional to D^2. As we have just seen, $\frac{P_{\text{fina}}}{P_{\text{initial}}} = \left(\frac{D_{\text{fina}}}{D_{\text{initial}}}\right)^2$. Initially, we have $P_{\text{initial}} = 10^6$ yr and $D_{\text{initial}} = 10^4$ AU. Then, if D_{final} is in AU, P_{final} (in years) is given by $P_{\text{fina}} = 0.01D^2_{\text{fina}}$. If Jupiter's orbit has a radius of 5.2 AU, then the diameter is 10.4 AU. The period is then 1.08 years.

Formation of the Terrestrial Planets

The grains that condensed in the solar nebula rather quickly joined into larger and larger chunks, until most of the solid material was in the form of *planetesimals,* chunks a few kilometers to a few tens of kilometers in diameter. Some planetesimals still survive today as comets and asteroids. Others have left their imprint on the cratered surfaces of many of the worlds we studied in earlier chapters. A substantial step up in size is required, however, to go from planetesimal to planet.

Some planetesimals were large enough to attract their neighbors gravitationally and thus to grow by the process called **accretion**. While the intermediate steps are not well understood, ultimately several dozen centers of accretion seem to have grown in the inner solar system. Each of these attracted surrounding planetesimals until it had acquired a mass similar to that of Mercury or Mars. At this stage, we may think of these objects as *protoplanets*—"not quite ready for prime time" planets.

Each of these protoplanets continued to grow by the accretion of planetesimals. Every incoming planetesimal was accelerated by the gravity of the protoplanet, striking with enough energy to melt both the projectile and a part of the impact area. Soon the entire protoplanet was heated to above the melting temperature of rocks.

The result was *planetary differentiation*, with heavier metals sinking toward the core and lighter silicates rising toward the surface. As they were heated, the inner protoplanets lost some of their more volatile constituents (the lighter gases), leaving more of the heavier elements and compounds behind.

Formation of the Giant Planets

In the outer solar system, where the available raw materials included ices as well as rocks, the protoplanets grew to be much larger, with masses ten times greater than Earth. These protoplanets of the outer solar system were so large that they were able to attract and hold the surrounding gas. As the hydrogen and helium rapidly collapsed onto their cores, the giant planets were heated by the energy of contraction. But although these giant planets got hotter than their terrestrial siblings, they were far too small to raise their central temperatures and pressures to the point where nuclear reactions could begin (and it is such reactions that give us our definition of a star). After glowing dull red for a few thousand years, the giant planets gradually cooled to their present state (**Figure 14.13**).

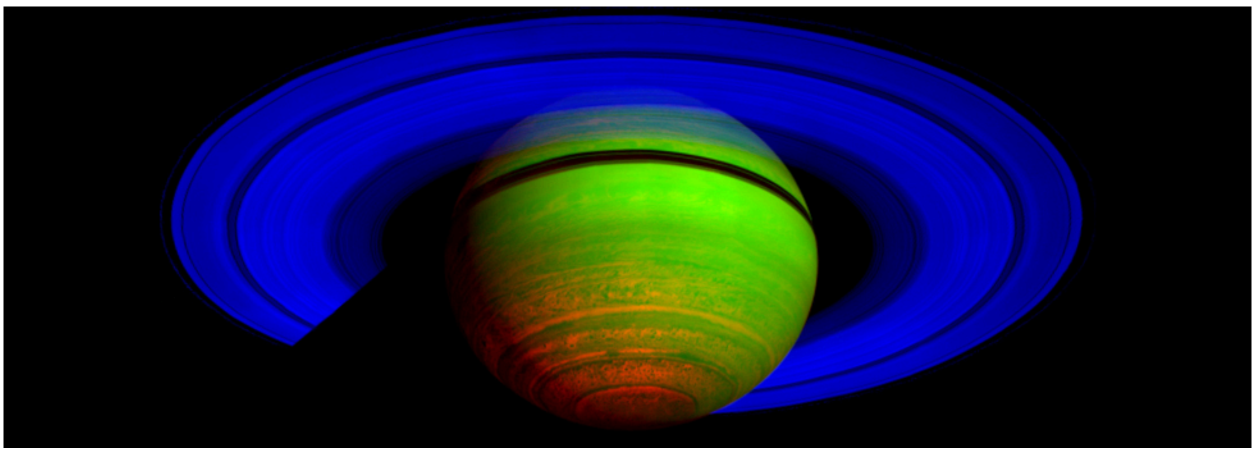


Figure 14.13 Saturn Seen in Infrared. This image from the Cassini spacecraft is stitched together from 65 individual observations. Sunlight reflected at a wavelength of 2 micrometers is shown as blue, sunlight reflected at 3 micrometers is shown as green, and heat radiated from Saturn's interior at 5 micrometers is red. For example, Saturn's rings reflect sunlight at 2 micrometers, but not at 3 and 5 micrometers, so they appear blue. Saturn's south polar regions are seen glowing with internal heat. (credit: modification of work by NASA/JPL/University of Arizona)

The collapse of gas from the nebula onto the cores of the giant planets explains how these objects acquired nearly the same hydrogen-rich composition as the Sun. The process was most efficient for Jupiter and Saturn; hence, their compositions are most nearly "cosmic." Much less gas was captured by Uranus and Neptune, which is why these two planets have compositions dominated by the icy and rocky building blocks that made up their large cores rather than by hydrogen and helium. The initial formation period ended when much of the available raw material was used up and the solar wind (the flow of atomic particles) from the young Sun blew away the remaining supply of lighter gases.

Further Evolution of the System

All the processes we have just described, from the collapse of the solar nebula to the formation of protoplanets, took place within a few million years. However, the story of the formation of the solar system was not complete at this stage; there were many planetesimals and other debris that did not initially accumulate to form the planets. What was their fate?

The comets visible to us today are merely the tip of the cosmic iceberg (if you'll pardon the pun). Most comets are believed to be in the Oort cloud, far from the region of the planets. Additional comets and icy dwarf planets are in the Kuiper belt, which stretches beyond the orbit of Neptune. These icy pieces probably formed near the present orbits of Uranus and Neptune but were ejected from their initial orbits by the gravitational influence of the giant planets.

In the inner parts of the system, remnant planetesimals and perhaps several dozen protoplanets continued to whiz about. Over the vast span of time we are discussing, collisions among these objects were inevitable. Giant impacts at this stage probably stripped Mercury of part of its mantle and crust, reversed the rotation of Venus, and broke off part of Earth to create the Moon (all events we discussed in other chapters).

Smaller-scale impacts also added mass to the inner protoplanets. Because the gravity of the giant planets could "stir up" the orbits of the planetesimals, the material impacting on the inner protoplanets could have come from almost anywhere within the solar system. In contrast to the previous stage of accretion, therefore, this new material did not represent just a narrow range of compositions.

As a result, much of the debris striking the inner planets was ice-rich material that had condensed in the outer part of the solar nebula. As this comet-like bombardment progressed, Earth accumulated the water and various organic compounds that would later be critical to the formation of life. Mars and Venus probably also acquired abundant water and organic materials from the same source, as Mercury and the Moon are still doing to form their icy polar caps.

Gradually, as the planets swept up or ejected the remaining debris, most of the planetesimals disappeared. In two regions, however, stable orbits are possible where leftover planetesimals could avoid impacting the planets or being ejected from the system. These regions are the asteroid belt between Mars and Jupiter and the Kuiper belt beyond Neptune. The planetesimals (and their fragments) that survive in these special locations are what we now call asteroids, comets, and trans-neptunian objects.

Astronomers used to think that the solar system that emerged from this early evolution was similar to what we see today. Detailed recent studies of the orbits of the planets and asteroids, however, suggest that there were more violent events soon afterward, perhaps involving substantial changes in the orbits of Jupiter and Saturn. These two giant planets control, through their gravity, the distribution of asteroids. Working backward from our present solar system, it appears that orbital changes took place during the first few hundred million years. One consequence may have been scattering of asteroids into the inner solar system, causing the period of "heavy bombardment" recorded in the oldest lunar craters.

14.4 COMPARISON WITH OTHER PLANETARY SYSTEMS

Learning Objectives

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

- Describe how the observations of protoplanetary disks provides evidence for the existence of other planetary systems
- Explain the two primary methods for detection of exoplanets
- Compare the main characteristics of other planetary systems with the features of the solar system

Until the middle 1990s, the practical study of the origin of planets focused on our single known example—the solar system. Although there had been a great deal of speculation about planets circling other stars, none had actually been detected. Logically enough, in the absence of data, most scientists assumed that our own system was likely to be typical. They were in for a big surprise.

Discovery of Other Planetary Systems

In **The Birth of Stars and the Discovery of Planets outside the Solar System**, we discuss the formation of stars and planets in some detail. Stars like our Sun are formed when dense regions in a molecular cloud (made of gas and dust) feel an extra gravitational force and begin to collapse. This is a runaway process: as the cloud collapses, the gravitational force gets stronger, concentrating material into a protostar. Roughly half of the time, the protostar will fragment or be gravitationally bound to other protostars, forming a binary or multiple star system—stars that are gravitationally bound and orbit each other. The rest of the time, the protostar collapses in isolation, as was the case for our Sun. In all cases, as we saw, conservation of angular momentum results in a spin-up of the collapsing protostar, with surrounding material flattened into a disk. Today, this kind of structure can actually be observed. The Hubble Space Telescope, as well as powerful new ground-based telescopes, enable astronomers to study directly the nearest of these *circumstellar disks* in regions of space where stars are being born today, such as the Orion Nebula (**Figure 14.14**) or the Taurus star-forming region.

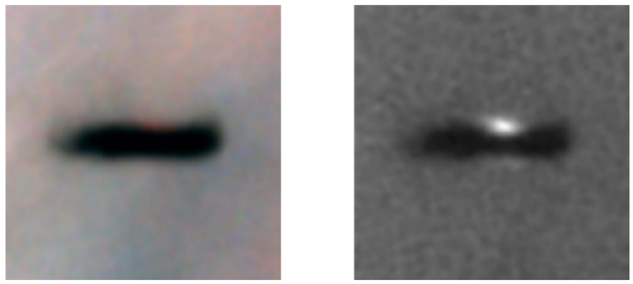
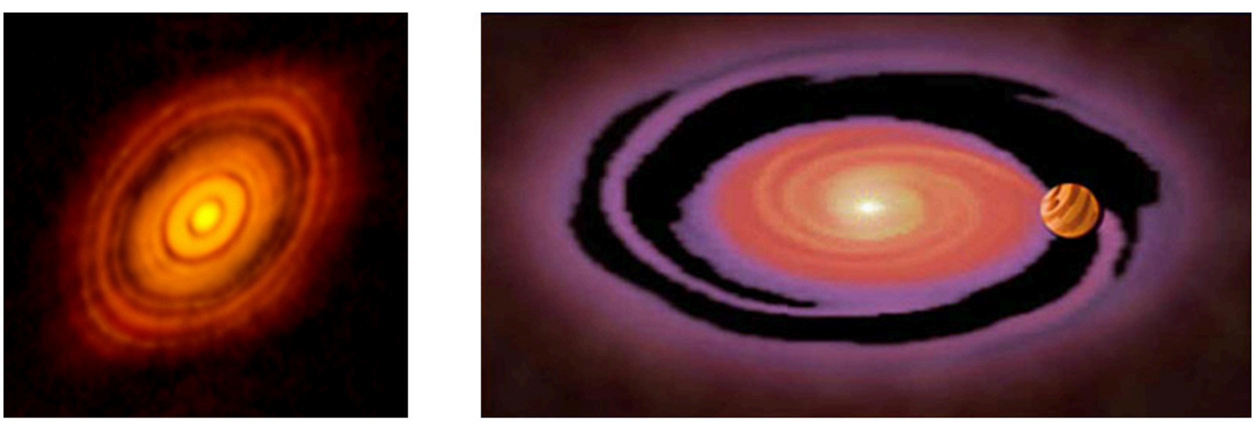


Figure 14.14 Protoplanetary Disk in the Orion Nebula. The Hubble Space Telescope imaged this protoplanetary disk in the Orion Nebula, a region of active star formation, using two different filters. The disk, about 17 times the size of our solar system, is in an edge-on orientation to us, and the newly formed star is shining at the center of the flattened dust cloud. The dark areas indicate absorption, not an absence of material. In the left image we see the light of the nebula and the dark cloud; in the right image, a special filter was used to block the light of the background nebula. You can see gas above and below the disk set to glow by the light of the newborn star hidden by the disk. (credit: modification of work by Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O'Dell (Rice University), and NASA)

Many of the circumstellar disks we have discovered show internal structure. The disks appear to be donut-shaped, with gaps close to the star. Such gaps indicate that the gas and dust in the disk have already collapsed to form large planets (**Figure 14.15**). The newly born protoplanets are too small and faint to be seen directly, but the depletion of raw materials in the gaps hints at the presence of something invisible in the inner part of the circumstellar disk—and that something is almost certainly one or more planets. Theoretical models of planet formation, like the one seen at right in **Figure 14.15**, have long supported the idea that planets would clear gaps as they form in disks.



(a) (b)

Figure 14.15 Protoplanetary Disk around HL Tau. (a) This image of a protoplanetary disk around HL Tau was taken with the Atacama Large Millimeter/submillimeter Array (ALMA), which allows astronomers to construct radio images that rival those taken with visible light. (b) Newly formed planets that orbit the central star clear out dust lanes in their paths, just as our theoretical models predict. This computer simulation shows the empty lane and spiral density waves that result as a giant planet is forming within the disk. The planet is not shown to scale. (credit a: modification of work by ALMA (ESO/NAOJ/NRAO); credit b: modification of work by NASA/ESA and A. Feild (STScI))

Our figure shows HL Tau, a one-million-year-old “newborn” star in the Taurus star-forming region. The star is embedded in a shroud of dust and gas that obscures our visible-light view of a circumstellar disk around the star. In 2014 astronomers obtained a dramatic view of the HL Tau circumstellar disk using millimeter waves, which pierce the cocoon of dust around the star, showing dust lanes being carved out by several newly formed protoplanets. As the mass of the protoplanets increases, they travel in their orbits at speeds that are faster than the dust and gas in the circumstellar disk. As the protoplanets plow through the disk, their gravitational reach begins to exceed their cross-sectional area, and they become very efficient at sweeping up material and growing until they clear a gap in the disk. The image of **Figure 14.15** shows us that a number of protoplanets are forming in the disk and that they were able to form faster than our earlier ideas had suggested—all in the first million years of star formation.

LINK TO LEARNING

For an explanation of ALMA’s ground-breaking observations of HL Tau and what they reveal about plant formation, watch this **videocast (https://openstaxcollege.org/l/30eusoobhltavid)** from the European Southern Observatory.

Discovering Exoplanets

You might think that with the advanced telescopes and detectors astronomers have today, they could directly image planets around nearby stars (which we call **exoplanets**). This has proved extremely difficult, however, not only because the exoplanets are faint, but also because they are generally lost in the brilliant glare of the star they orbit. As we discuss in more detail in **The Birth of Stars and the Discovery of Planets outside the Solar System**, the detection techniques that work best are indirect: they observe the effects of the planet on the star it orbits, rather than seeing the planet itself.

The first technique that yielded many planet detections is very high-resolution stellar spectroscopy. The *Doppler effect* lets astronomers measure the star’s *radial velocity:* that is, the speed of the star, toward us or away from us, relative to the observer. If there is a massive planet in orbit around the star, the gravity of the planet causes the star to wobble, changing its radial velocity by a small but detectable amount. The distance of the star does not matter, as long as it is bright enough for us to take very high quality spectra.

Measurements of the variation in the star’s radial velocity as the planet goes around the star can tell us the mass and orbital period of the planet. If there are several planets present, their effects on the radial velocity can be disentangled, so the entire planetary system can be deciphered—as long as the planets are massive enough to produce a measureable Doppler effect. This detection technique is most sensitive to large planets orbiting close to the star, since these produce the greatest wobble in their stars. It has been used on large ground-based telescopes to detect hundreds of planets, including one around Proxima Centauri, the nearest star to the Sun.

The second indirect technique is based on the slight dimming of a star when one of its planets *transits*, or crosses over the face of the star, as seen from Earth. Astronomers do not see the planet, but only detect its presence from careful measurements of a change in the brightness of the star over long periods of time. If the slight dips in brightness repeat at regular intervals, we can determine the orbital period of the planet. From the amount of starlight obscured, we can measure the planet’s size.

While some transits have been measured from Earth, large-scale application of this transit technique requires a telescope in space, above the atmosphere and its distortions of the star images. It has been most successfully applied from the NASA Kepler space observatory, which was built for the sole purpose of "staring" for 5 years at a single part of the sky, continuously monitoring the light from more than 150,000 stars. The primary goal of Kepler was to determine the frequency of occurrence of exoplanets of different sizes around different classes of stars. Like the Doppler technique, the transit observations favor discovery of large planets and short-period orbits.

Recent detection of exoplanets using both the Doppler and transit techniques has been incredibly successful. Within two decades, we went from no knowledge of other planetary systems to a catalog of *thousands* of exoplanets. Most of the exoplanets found so far are more massive than or larger in size than Earth. It is not that Earth analogs do not exist. Rather, the shortage of small rocky planets is an observational bias: smaller planets are more difficult to detect.

Analyses of the data to correct for such biases or selection effects indicate that small planets (like the terrestrial planets in our system) are actually much more common than giant planets. Also relatively common are "super Earths," planets with two to ten times the mass of our planet (Figure 14.16). We don't have any of these in our solar system, but nature seems to have no trouble making them elsewhere. Overall, the Kepler data suggest that approximately one quarter of stars have exoplanet systems, implying the existence of at least 50 billion planets in our Galaxy alone.

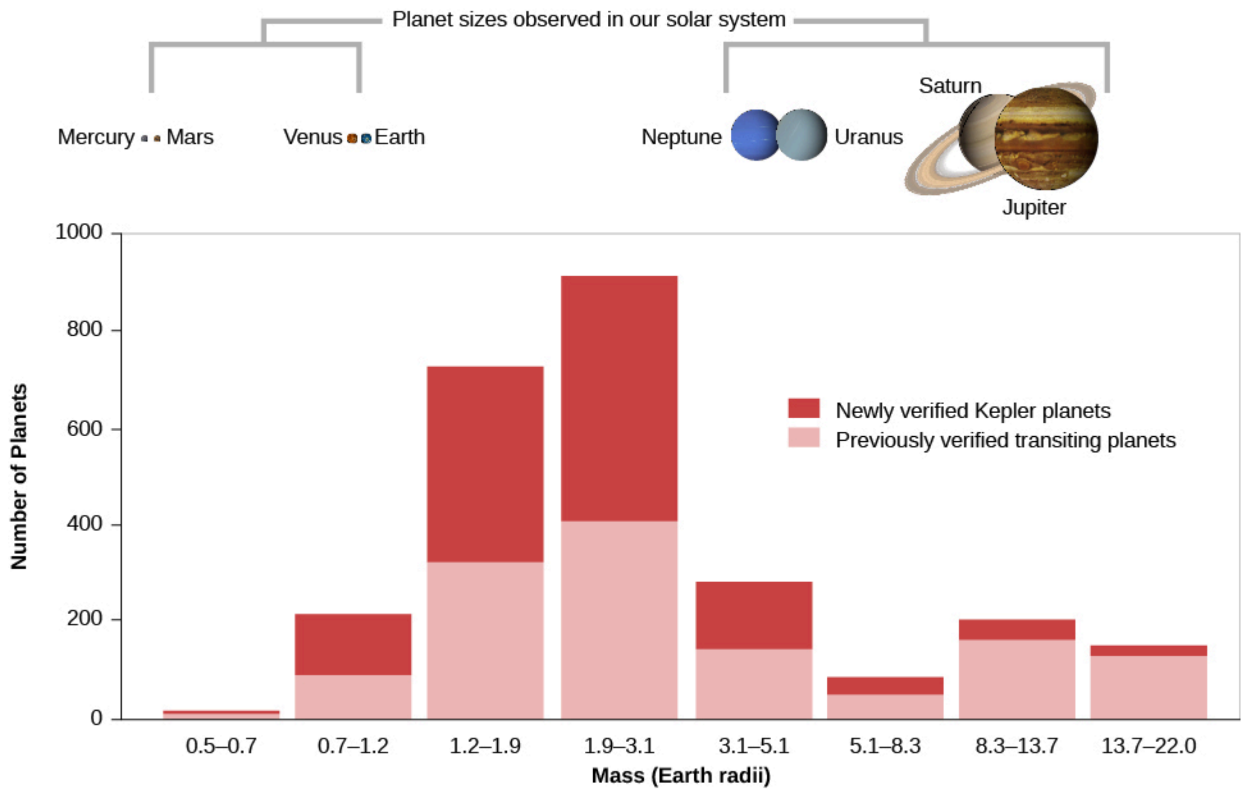


Figure 14.16 Transiting Planets by Size. This bar graph shows the planets found so far using the transit method (the vast majority found by the Kepler mission). The orange parts of each bar indicate the planets announced by the Kepler team in May 2016. Note that the largest number of planets found so far are in two categories that we don't have in our own solar system—planets whose size is between Earth's and Neptune's. (credit: modification of work by NASA)

The Configurations of Other Planetary Systems

Let's look more closely at the progress in the detection of exoplanets. Figure 14.17 shows the planets that were discovered each year by the two techniques we discussed. In the early years of exoplanet discovery, most of the planets were similar in mass to Jupiter. This is because, as mentioned above, the most massive planets were easiest to detect. In more recent years, planets smaller than Neptune and even close to the size of Earth have been detected.

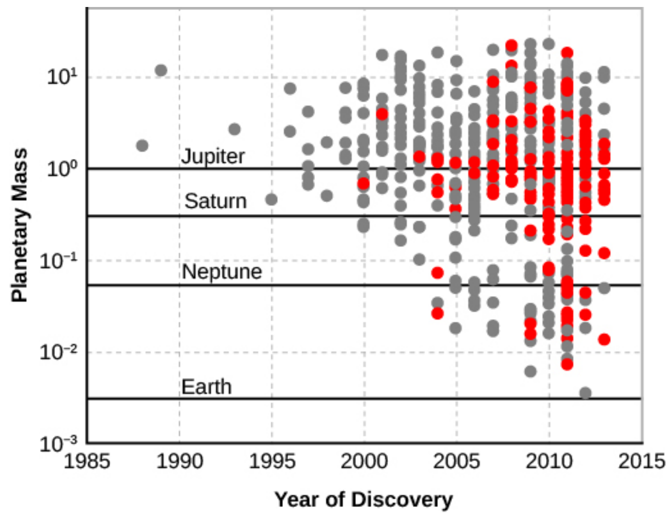


Figure 14.17 Masses of Exoplanets Discovered by Year. Horizontal lines are drawn to reference the masses of Jupiter, Saturn, Neptune, and Earth. The gray dots indicate planets discovered by measuring the radial velocity of the star, and the red dots are for planets that transit their stars. In the early years, the only planets that could be detected were similar in mass to Jupiter. Improvements in technology and observing strategies enabled the detection of lower mass planets as time went on, and now even smaller worlds are being found. (Note that this tally ends in 2014.)

We also know that many exoplanets are in multiplanet systems. This is one characteristic that our solar system shares with exosystems. Looking back at Figure 14.15 and seeing how such large disks can give rise to more than one center of condensation, it is not too surprising that multiplanet systems are a typical outcome of planet formation. Astronomers have tried to measure whether multiple planet systems all lie in the same plane using astrometry. This is a difficult measurement to make with current technology, but it is an important measurement that could help us understand the origin and evolution of planetary systems.

Comparison between Theory and Data

Many of the planetary systems discovered so far do not resemble our own solar system. Consequently, we have had to reassess some aspects of the “standard models” for the formation of planetary systems. Science sometimes works in this way, with new data contradicting our expectations. The press often talks about a scientist making experiments to “confirm” a theory. Indeed, it is comforting when new data support a hypothesis or theory and increase our confidence in an earlier result. But the most exciting and productive moments in science often come when new data *don’t* support existing theories, forcing scientists to rethink their position and develop new and deeper insights into the way nature works.

Nothing about the new planetary systems contradicts the basic idea that planets form from the aggregation (clumping) of material within circumstellar disks. However, the existence of “ hot Jupiters”—planets of jovian mass that are closer to their stars than the orbit of Mercury—poses the biggest problem. As far as we know, a giant planet cannot be formed without the condensation of water ice, and water ice is not stable so close to the heat of a star. It seems likely that all the giant planets, “hot” or “normal,” formed at a distance of several astronomical units from the star, but we now see that they did not necessarily stay there. This discovery has led to a revision in our understanding of planet formation that now includes “planet migrations” within the protoplanetary disk, or later gravitational encounters between sibling planets that scatter one of the planets inward.

Many exoplanets have large orbital eccentricity (recall this means the orbits are not circular). High eccentricities were not expected for planets that form in a disk. This discovery provides further support for the scattering of planets when they interact gravitationally. When planets change each other's motions, their orbits could become much more eccentric than the ones with which they began.

There are several suggestions for ways migration might have occurred. Most involve interactions between the giant planets and the remnant material in the circumstellar disk from which they formed. These interactions would have taken place when the system was very young, while material still remained in the disk. In such cases, the planet travels at a faster velocity than the gas and dust and feels a kind of "headwind" (or friction) that causes it to lose energy and spiral inward. It is still unclear how the spiraling planet stops before it plunges into the star. Our best guess is that this plunge into the star is the fate for many protoplanets; however, clearly some migrating planets can stop their inward motions and escape this destruction, since we find hot Jupiters in many mature planetary systems.

14.5 PLANETARY EVOLUTION

Learning Objectives

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

- Describe the geological activity during the evolution of the planets, particularly on the terrestrial planets
- Describe the factors that affect differences in elevation on the terrestrial planets
- Explain how the differences in atmosphere on Venus, Earth, and Mars evolved from similar starting points in the early history of the solar system

While we await more discoveries and better understanding of other planetary systems, let us look again at the early history of our own solar system, after the dissipation of our dust disk. The era of giant impacts was probably confined to the first 100 million years of solar system history, ending by about 4.4 billion years ago. Shortly thereafter, the planets cooled and began to assume their present aspects. Up until about 4 billion years ago, they continued to acquire volatile materials, and their surfaces were heavily cratered from the remaining debris that hit them. However, as external influences declined, all the terrestrial planets as well as the moons of the outer planets began to follow their own evolutionary courses. The nature of this evolution depended on each object's composition, mass, and distance from the Sun.

Geological Activity

We have seen a wide range in the level of geological activity on the terrestrial planets and icy moons. Internal sources of such activity (as opposed to pummeling from above) require energy, either in the form of primordial heat left over from the formation of a planet or from the decay of radioactive elements in the interior. The larger the planet or moon, the more likely it is to retain its internal heat and the more slowly it cools—this is the "baked potato effect" mentioned in **Other Worlds: An Introduction to the Solar System**. Therefore, we are more likely to see evidence of continuing geological activity on the surface of larger (solid) worlds (**Figure 14.18**). Jupiter's moon Io is an interesting exception to this rule; we saw that it has an unusual source of heat from the gravitational flexing of its interior by the tidal pull of Jupiter. Europa is probably also heated by jovian tides. Saturn may be having a similar effect on its moon Enceladus.

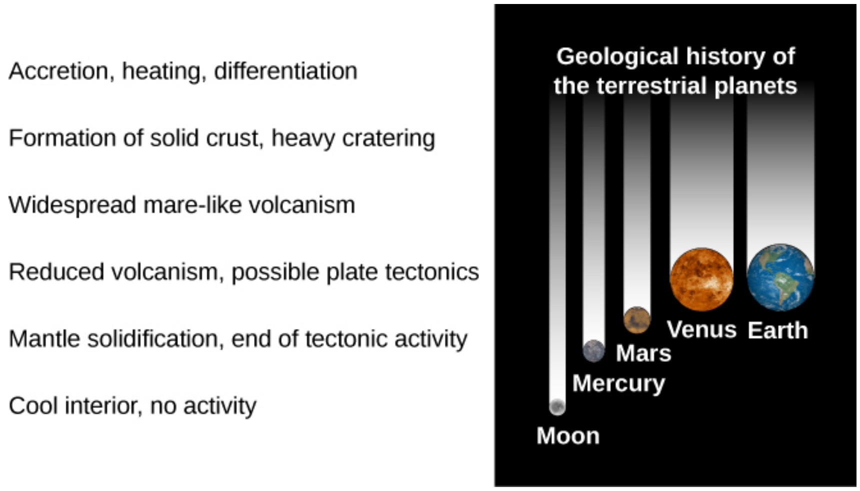


Figure 14.18 Stages in the Geological History of a Terrestrial Planet. In this image, time increases downward along the left side, where the stages are described. Each planet is shown roughly in its present stage. The smaller the planet, the more quickly it passes through these stages.

The Moon, the smallest of the terrestrial worlds, was internally active until about 3.3 billion years ago, when its major volcanism ceased. Since that time, its mantle has cooled and become solid, and today even internal seismic activity has declined to almost zero. The Moon is a geologically dead world. Although we know much less about Mercury, it seems likely that this planet, too, ceased most volcanic activity about the same time the Moon did.

Mars represents an intermediate case, and it has been much more active than the Moon. The southern hemisphere crust had formed by 4 billion years ago, and the northern hemisphere volcanic plains seem to be contemporary with the lunar maria. However, the Tharsis bulge formed somewhat later, and activity in the large Tharsis volcanoes has apparently continued on and off to the present era.

Earth and Venus are the largest and most active terrestrial planets. Our planet experiences global plate tectonics driven by convection in its mantle. As a result, our surface is continually reworked, and most of Earth's surface material is less than 200 million years old. Venus has generally similar levels of volcanic activity, but unlike Earth, it has not experienced plate tectonics. Most of its surface appears to be no more than 500 million years old. We did see that the surface of our sister planet is being modified by a kind of "blob tectonics"—where hot material from below puckers and bursts through the surface, leading to coronae, pancake volcanoes, and other such features. A better understanding of the geological differences between Venus and Earth is a high priority for planetary geologists.

The geological evolution of the icy moons and Pluto has been somewhat different from that of the terrestrial planets. Tidal energy sources have been active, and the materials nature has to work with are not the same. On these outer worlds, we see evidence of low-temperature volcanism, with the silicate lava of the inner planets being supplemented by sulfur compounds on Io, and replaced by water and other ices on Pluto and other outer-planet moons.

Elevation Differences

Let's look at some specific examples of how planets differ. The mountains on the terrestrial planets owe their origins to different processes. On the Moon and Mercury, the major mountains are ejecta thrown up by the large basin-forming impacts that took place billions of years ago. Most large mountains on Mars are volcanoes, produced by repeated eruptions of lava from the same vents. There are similar (but smaller) volcanoes on Earth and Venus. However, the highest mountains on Earth and Venus are the result of compression and uplift of the surface. On Earth, this crustal compression results from collisions of one continental plate with another.

It is interesting to compare the maximum heights of the volcanoes on Earth, Venus, and Mars (**Figure 14.19**). On Venus and Earth, the maximum elevation differences between these mountains and their surroundings are about 10 kilometers. Olympus Mons, in contrast, towers more than 20 kilometers above its surroundings and nearly 30 kilometers above the lowest elevation areas on Mars.

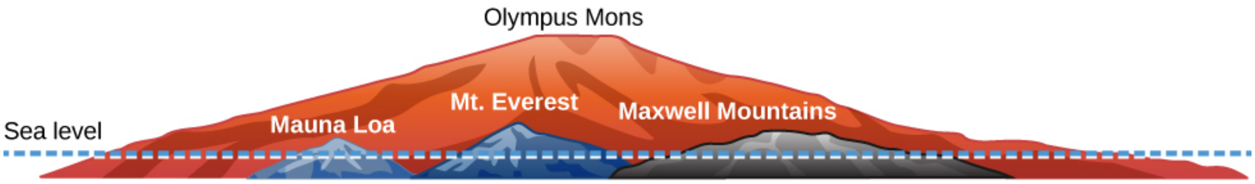


Figure 14.19 Highest Mountains on Mars, Venus, and Earth. Mountains can rise taller on Mars because Mars has less surface gravity and no moving plates. The vertical scale is exaggerated by a factor of three to make comparison easier. The label "sea level" refers only to Earth, of course, since the other two planets don't have oceans. Mauna Loa and Mt. Everest are on Earth, Olympus Mons is on Mars, and the Maxwell Mountains are on Venus.

One reason Olympus Mons (**Figure 14.20**) is so much higher than its terrestrial counterparts is that the crustal plates on Earth never stop moving long enough to let a really large volcano grow. Instead, the moving plate creates a long row of volcanoes like the Hawaiian Islands. On Mars (and perhaps Venus) the crust remains stationary with respect to the underlying hot spot, and so a single volcano can continue to grow for hundreds of millions of years.

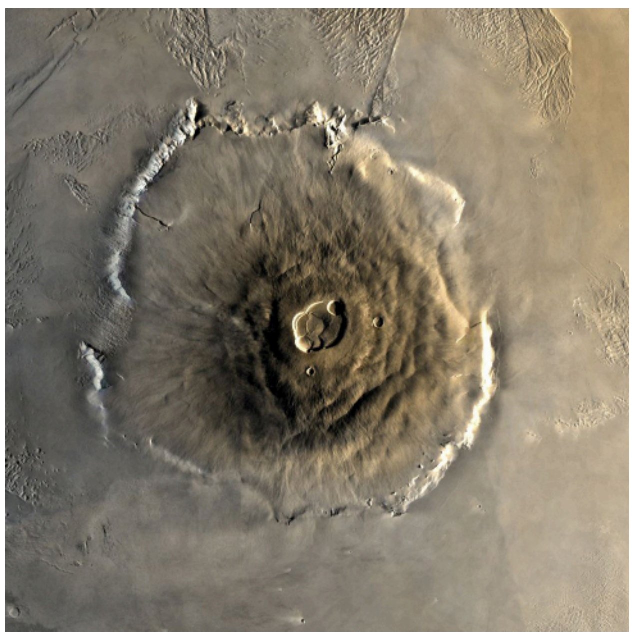


Figure 14.20 Olympus Mons. The largest martian volcano is seen from above in this spectacular composite image created from many Viking orbiter photographs. The volcano is nearly 500 kilometers wide at its base and more than 20 kilometers high. (Its height is almost three times the height of the tallest mountain on Earth.) (credit: modification of work by NASA/USGS)

A second difference relates to the strength of gravity on the three planets. The surface gravity on Venus is nearly the same as that on Earth, but on Mars it is only about one third as great. In order for a mountain to survive, its internal strength must be great enough to support its weight against the force of gravity. Volcanic rocks have known strengths, and we can calculate that on Earth, 10 kilometers is about the limit. For instance, when new lava is added to the top of Mauna Loa in Hawaii, the mountain slumps downward under its own weight. The same height limit applies on Venus, where the force of gravity is the same as Earth's. On Mars, however, with its lesser surface gravity, much greater elevation differences can be supported, which helps explain why Olympus Mons is more than twice as high as the tallest mountains of Venus or Earth.

By the way, the same kind of calculation that determines the limiting height of a mountain can be used to ascertain the largest body that can have an irregular shape. Gravity, if it can, pulls all objects into the most "efficient" shape (where all the outside points are equally distant from the center). All the planets and larger moons are nearly spherical, due to the force of their own gravity pulling them into a sphere. But the smaller the object, the greater the departure from spherical shape that the strength of its rocks can support. For silicate bodies, the limiting diameter is about 400 kilometers; larger objects will always be approximately spherical, while smaller ones can have almost any shape (as we see in photographs of asteroids, such as **Figure 14.21**).

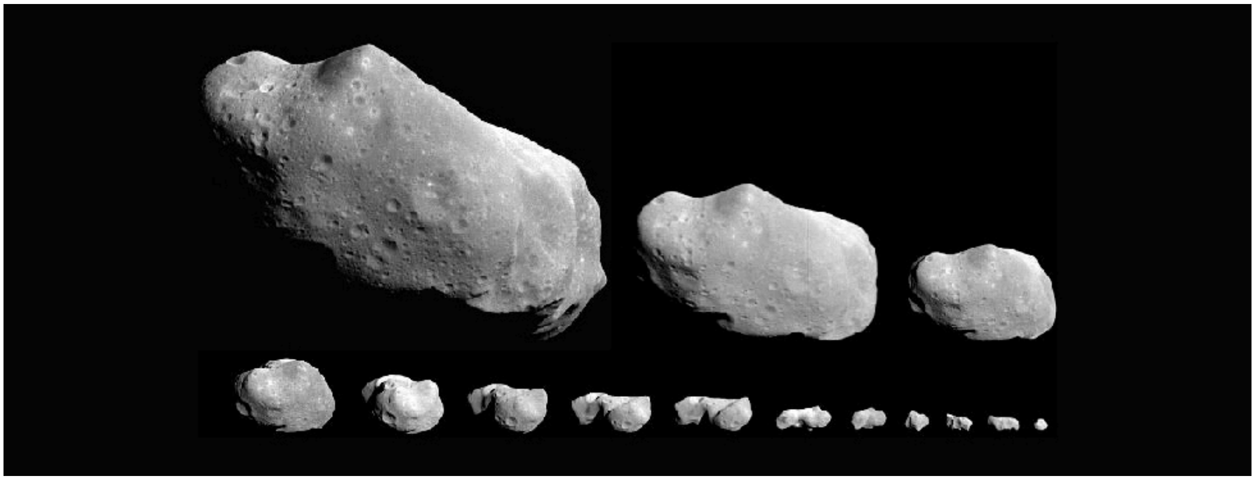


Figure 14.21 Irregular Asteroid. Small objects such as asteroid Ida (shown here in multiple views taken by the Galileo spacecraft camera as it flew past) are generally irregular or elongated; they do not have strong enough gravity to pull them into a spherical shape. Ida is about 60 kilometers long in its longest dimension. (credit: modification of work by NASA/JPL)

Atmospheres

The atmospheres of the planets were formed by a combination of gas escaping from their interiors and the impacts of volatile-rich debris from the outer solar system. Each of the terrestrial planets must have originally had similar atmospheres, but Mercury was too small and too hot to retain its gas. The Moon probably never had an atmosphere since the material composing it was depleted in volatile materials.

The predominant volatile gas on the terrestrial planets is now carbon dioxide (CO_2), but initially there were probably also hydrogen-containing gases. In this more chemically *reduced* (hydrogen-dominated) environment, there should have been large amounts of carbon monoxide (CO) and traces of ammonia (NH_3) and methane (CH_4). Ultraviolet light from the Sun split apart the molecules of reducing gases in the inner solar system, however. Most of the light hydrogen atoms escaped, leaving behind the oxidized (oxygen-dominated) atmospheres we see today on Earth, Venus, and Mars.

The fate of water was different on each of these three planets, depending on its size and distance from the Sun. Early in its history, Mars apparently had a thick atmosphere with abundant liquid water, but it could not retain those conditions. The CO_2 necessary for a substantial greenhouse effect was lost, the temperature dropped, and eventually the remaining water froze. On Venus the reverse process took place, with a runaway greenhouse effect leading to the permanent loss of water. Only Earth managed to maintain the delicate balance that permits liquid water to persist on its surface.

With the water gone, Venus and Mars each ended up with an atmosphere of about 96 percent carbon dioxide and a few percent nitrogen. On Earth, the presence first of water and then of life led to a very different kind of atmosphere. The CO_2 was removed and deposited in marine sediment. The proliferation of life forms that could photosynthesize eventually led to the release of more oxygen than natural chemical reactions can remove from the atmosphere. As a result, thanks to the life on its surface, Earth finds itself with a great deficiency of CO_2, with nitrogen as the most abundant gas, and the only planetary atmosphere that contains free oxygen.

In the outer solar system, Titan is the only moon with a substantial atmosphere. This object must have contained sufficient volatiles—such as ammonia, methane, and nitrogen—to form an atmosphere. Thus, today Titan’s atmosphere consists primarily of nitrogen. Compared with those on the inner planets, temperatures on Titan are too low for either carbon dioxide or water to be in vapor form. With these two common volatiles frozen solid, it is perhaps not too surprising that nitrogen has ended up as the primary atmospheric constituent.

We see that nature, starting with one set of chemical constituents, can fashion a wide range of final atmospheres appropriate to the conditions and history of each world. The atmosphere we have on Earth is the result of many eons of evolution and adaptation. And, as we saw, it can be changed by the actions of the life forms that inhabit the planet.

One of the motivations for exploration of our planetary system is the search for life, beginning with a survey for potentially habitable environments. Mercury, Venus, and the Moon are not suitable; neither are most of the moons in the outer solar system. The giant planets, which do not have solid surfaces, also fail the test for habitability.

So far, the search for habitable environments has focused on the presence of liquid water. Earth and Europa both have large oceans, although Europa’s ocean is covered with a thick crust of ice. Mars has a long history of liquid water on its surface, although the surface today is mostly dry and cold. However, there is strong evidence for subsurface water on Mars, and even today water flows briefly on the surface under the right conditions. Enceladus may have the most accessible liquid water, which is squirting into space by means of the geysers observed with our Cassini spacecraft. Titan is in many ways the most interesting world we have explored. It is far too cold for liquid water, but with its thick atmosphere and hydrocarbon lakes, it may be the best place to search for “life as we don’t know it.”

We now come to the end of our study of the planetary system. Although we have learned a great deal about the other planets during the past few decades of spacecraft exploration, much remains unknown. Discoveries in recent years of geological activity on Titan and Enceladus were unexpected, as was the complex surface of Pluto revealed by New Horizons. The study of exoplanetary systems provides a new perspective, teaching us that there is much more variety among planetary systems than scientists had imagined a few decades ago. The exploration of the solar system is one of the greatest human adventures, and, in many ways, it has just begun.

CHAPTER 14 REVIEW

KEY TERMS

accretion the gradual accumulation of mass, as by a planet forming from colliding particles in the solar nebula

exoplanet a planet orbiting a star other than our Sun

iron meteorite a meteorite composed primarily of iron and nickel

meteor a small piece of solid matter that enters Earth's atmosphere and burns up, popularly called a *shooting star* because it is seen as a small flash of light

meteor shower many meteors appearing to radiate from one point in the sky; produced when Earth passes through a cometary dust stream

meteorite a portion of a meteor that survives passage through the atmosphere and strikes the ground

stony meteorite a meteorite composed mostly of stony material, either primitive or differentiated

stony-iron meteorite a type of differentiated meteorite that is a blend of nickel-iron and silicate materials

SUMMARY

14.1 Meteors

When a fragment of interplanetary dust strikes Earth's atmosphere, it burns up to create a meteor. Streams of dust particles traveling through space together produce meteor showers, in which we see meteors diverging from a spot in the sky called the radiant of the shower. Many meteor showers recur each year and are associated with particular comets that have left dust behind as they come close to the Sun and their ices evaporate (or have broken up into smaller pieces).

14.2 Meteorites: Stones from Heaven

Meteorites are the debris from space (mostly asteroid fragments) that survive to reach the surface of Earth. Meteorites are called *finds* or *falls* according to how they are discovered; the most productive source today is the Antarctic ice cap. Meteorites are classified as irons, stony-irons, or stones accordingly to their composition. Most stones are primitive objects, dated to the origin of the solar system 4.5 billion years ago. The most primitive are the carbonaceous meteorites, such as Murchison and Allende. These can contain a number of organic (carbon-rich) molecules.

14.3 Formation of the Solar System

A viable theory of solar system formation must take into account motion constraints, chemical constraints, and age constraints. Meteorites, comets, and asteroids are survivors of the solar nebula out of which the solar system formed. This nebula was the result of the collapse of an interstellar cloud of gas and dust, which contracted (conserving its angular momentum) to form our star, the Sun, surrounded by a thin, spinning disk of dust and vapor. Condensation in the disk led to the formation of planetesimals, which became the building blocks of the planets. Accretion of infalling materials heated the planets, leading to their differentiation. The giant planets were also able to attract and hold gas from the solar nebula. After a few million years of violent impacts, most of the debris was swept up or ejected, leaving only the asteroids and cometary remnants surviving to the present.

14.4 Comparison with Other Planetary Systems

The first planet circling a distant solar-type star was announced in 1995. Twenty years later, thousands of exoplanets have been identified, including planets with sizes and masses between Earth's and Neptune's, which we don't have in our own solar system. A few percent of exoplanet systems have "hot Jupiters," massive planets that orbit close to their stars, and many exoplanets are also in eccentric orbits. These two characteristics are fundamentally different from the attributes of gas giant planets in our own solar system and suggest that giant planets can migrate inward from their place of formation where it is cold enough for ice to form. Current data indicate that small (terrestrial type) rocky planets are common in our Galaxy; indeed, there must be tens of billions of such earthlike planets.

14.5 Planetary Evolution

After their common beginning, each of the planets evolved on its own path. Different possible outcomes are illustrated by comparison of the terrestrial planets (Earth, Venus, Mars, Mercury, and the Moon). All are rocky, differentiated objects. The level of geological activity is proportional to mass: greatest for Earth and Venus, less for Mars, and absent for the Moon and Mercury. However, tides from another nearby world can also generate heat to drive geological activity, as shown by Io, Europa, and Enceladus. Pluto is also active, to the surprise of planetary scientists. On the surfaces of solid worlds, mountains can result from impacts, volcanism, or uplift. Whatever their origin, higher mountains can be supported on smaller planets that have less surface gravity. The atmospheres of the terrestrial planets may have acquired volatile materials from comet impacts. The Moon and Mercury lost their atmospheres; most volatiles on Mars are frozen due to its greater distance from the Sun and its thinner atmosphere; and Venus retained CO_2 but lost H_2O when it developed a massive greenhouse effect. Only Earth still has liquid water on its surface and hence can support life.

FOR FURTHER EXPLORATION

Note: Resources about exoplanets are provided in **The Birth of Stars and the Discovery of Planets outside the Solar System**.

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Meteors and Meteorites

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Kring, D. "Unlocking the Solar System's Past." *Astronomy* (August 2006): 32. Part of a special issue devoted to meteorites.

Rubin, A. "Secrets of Primitive Meteorites." *Scientific American* (February 2013): 36. What they can teach us about the environment in which the solar system formed.

Evolution of the Solar System and Protoplanetary Disks

Jewitt, D., & Young, E. "Oceans from the Skies." *Scientific American* (March 2015): 36–43. How did Earth and the other inner planets get their water after the initial hot period?

Talcott, R. "How the Solar System Came to Be." *Astronomy* (November 2012): 24. On the formation period of the Sun and the planets.

Young, E. "Cloudy with a Chance of Stars." *Scientific American* (February 2010): 34. On how clouds of interstellar matter turn into star systems.

Websites

Meteors and Meteorites

American Meteor Society: **http://www.amsmeteors.org/ (http://www.amsmeteors.org/)** . For serious observers.

British and Irish Meteorite Society: **http://www.bimsociety.org/meteorites1.shtml (http://www.bimsociety.org/meteorites1.shtml)** .

Meteor Showers Online: **http://meteorshowersonline.com/ (http://meteorshowersonline.com/)** . By Gary Kronk.

Meteorite Information: **http://www.meteorite-information.com/ (http://www.meteorite-information.com/)** . A great collection of links for understanding and even collecting meteorites.

Meteorites from Mars: **http://www2.jpl.nasa.gov/snc/ (http://www2.jpl.nasa.gov/snc/)** . A listing and links from the Jet Propulsion Lab.

Meteors and Meteor Showers: **http://www.astronomy.com/observing/observe-the-solar-system/2010/04/meteors-and-meteor-showers (http://www.astronomy.com/observing/observe-the-solar-system/2010/04/meteors-and-meteor-showers)** . From *Astronomy* magazine.

Meteors: **http://www.skyandtelescope.com/observing/celestial-objects-to-watch/meteors/ (http://www.skyandtelescope.com/observing/celestial-objects-to-watch/meteors/)** . A collection of articles on meteor observing from *Sky & Telescope* magazine.

Nine Planets Meteorites and Meteors Page: **http://nineplanets.org/meteorites.html (http://nineplanets.org/meteorites.html)** .

Some Interesting Meteorite Falls of the Last Two Centuries: **http://www.icq.eps.harvard.edu/meteorites-1.html (http://www.icq.eps.harvard.edu/meteorites-1.html)** .

Evolution of the Solar System and Protoplanetary Disks

Circumstellar Disk Learning Site: **http://www.disksite.com/ (http://www.disksite.com/)** . By Dr. Paul Kalas.

Disk Detective Project: **http://www.diskdetective.org/ (http://www.diskdetective.org/)** . The WISE mission is asking the public to help them find protoplanetary disks in their infrared data.

Videos

Meteors and Meteorites

Meteorites and Meteor-wrongs: **https://www.youtube.com/watch?v=VQO335Y3zXo (https://www.youtube.com/watch?v=VQO335Y3zXo)** . Video with Dr. Randy Korotev of Washington U. in St. Louis (7:05).

Rare Meteorites from London’s Natural History Museum: **https://www.youtube.com/watch?v=w-Rsk-ywN44 (https://www.youtube.com/watch?v=w-Rsk-ywN44)** . A tour of the meteorite collection with curator Caroline Smith (18:22). Also see a short news piece about a martian meteorite: **https://www.youtube.com/watch?v=1EMR2r53f2s (https://www.youtube.com/watch?v=1EMR2r53f2s)** (2:54).

What Is a Meteor Shower (and How to Watch Them): **https://www.youtube.com/watch?v=xNmgvlwInCA (https://www.youtube.com/watch?v=xNmgvlwInCA)** . Top tips for watching meteor showers from the At-Bristol Science Center (3:18).

Evolution of the Solar System and Protoplanetary Disks

Origins of the Solar System: **http://www.pbs.org/wgbh/nova/space/origins-solar-system.html (http://www.pbs.org/wgbh/nova/space/origins-solar-system.html)** . Video from Nova ScienceNow narrated by Neil deGrasse Tyson (13:02).

Where Do Planets Come From?: **https://www.youtube.com/watch?v=zdIJUdZWlXo (https://www.youtube.com/watch?v=zdIJUdZWlXo)** . Public talk by Anjali Tripathi in March 2016 in the Center for Astrophysics Observatory Nights Series (56:14).

COLLABORATIVE GROUP ACTIVITIES

A. Ever since the true (cosmic) origin of meteorites was understood, people have tried to make money selling them to museums and planetariums. More recently, a growing number of private collectors have been interested in purchasing meteorite fragments, and a network of dealers (some more reputable than others) has sprung up to meet this need. What does your group think of all this? Who should own a meteorite? The person on whose land it falls, the person who finds it, or the local, state, or federal government where it falls? What if it falls on public land? Should there be any limit to what people charge for meteorites? Or should all meteorites be the common property of humanity? (If you can, try to research what the law is now in your area. See, for example, http://www.space.com/18009-meteorite-collectors-public-lands-rules.html.)

B. Your group has been formed to advise a very rich person who wants to buy some meteorites but is afraid of being cheated and sold some Earth rocks. How would you advise your client to make sure that the meteorites she buys are authentic?

C. Your group is a committee set up to give advice to NASA about how to design satellites and telescopes in space to minimize the danger of meteor impacts. Remember that the heavier a satellite is, the harder (more expensive) it is to launch. What would you include in your recommendations?

D. Discuss what you would do if you suddenly found that a small meteorite had crashed in or near your home. Whom would you call first, second, third? What would you do with the sample? (And would any damage to your home be covered by your insurance?)

E. A friend of your group really wants to see a meteor shower. The group becomes a committee to assist her in fulfilling this desire. What time of year would be best? What equipment would you recommend she gets? What advice would you give her?

F. Work with your group to find a table of the phases of the Moon for the next calendar year. Then look at the table of well-known meteor showers in this chapter and report on what phase the Moon will be in during each shower. (The brighter the Moon is in the night sky, the harder it is to see the faint flashes of meteors.)

G. Thinking that all giant planets had to be far from their stars (because the ones in our solar system are) is an example of making theories without having enough data (or examples). Can your group make a list of other instances in science (and human relations) where we have made incorrect judgments without having explored enough examples?

H. Have your group list and then discuss several ways in which the discovery of a diverse group of exoplanets (planets orbiting other stars) has challenged our conventional view of the formation of planetary systems like our solar system.

EXERCISES

Review Questions

1. A friend of yours who has not taken astronomy sees a meteor shower (she calls it a bunch of shooting stars). The next day she confides in you that she was concerned that the stars in the Big Dipper (her favorite star pattern) might be the next ones to go. How would you put her mind at ease?

2. In what ways are meteorites different from meteors? What is the probable origin of each?

3. How are comets related to meteor showers?

4. What do we mean by primitive material? How can we tell if a meteorite is primitive?

5. Describe the solar nebula, and outline the sequence of events within the nebula that gave rise to the planetesimals.

6. Why do the giant planets and their moons have compositions different from those of the terrestrial planets?

7. How do the planets discovered so far around other stars differ from those in our own solar system? List at least two ways.

8. Explain the role of impacts in planetary evolution, including both giant impacts and more modest ones.

9. Why are some planets and moons more geologically active than others?

10. Summarize the origin and evolution of the atmospheres of Venus, Earth, and Mars.

11. Why do meteors in a meteor shower appear to come from just one point in the sky?

Thought Questions

12. What methods do scientists use to distinguish a meteorite from terrestrial material?

13. Why do iron meteorites represent a much higher percentage of finds than of falls?

14. Why is it more useful to classify meteorites according to whether they are primitive or differentiated rather than whether they are stones, irons, or stony-irons?

15. Which meteorites are the most useful for defining the age of the solar system? Why?

16. Suppose a new primitive meteorite is discovered (sometime after it falls in a field of soybeans) and analysis reveals that it contains a trace of amino acids, all of which show the same rotational symmetry (unlike the Murchison meteorite). What might you conclude from this finding?

17. How do we know when the solar system formed? Usually we say that the solar system is 4.5 billion years old. To what does this age correspond?

18. We have seen how Mars can support greater elevation differences than Earth or Venus. According to the same arguments, the Moon should have higher mountains than any of the other terrestrial planets, yet we know it does not. What is wrong with applying the same line of reasoning to the mountains on the Moon?

19. Present theory suggests that giant planets cannot form without condensation of water ice, which becomes vapor at the high temperatures close to a star. So how can we explain the presence of jovian-sized exoplanets closer to their star than Mercury is to our Sun?

20. Why are meteorites of primitive material considered more important than other meteorites? Why have most of them been found in Antarctica?

Figuring For Yourself

21. How long would material take to go around if the solar nebula in **Example 14.1** became the size of Earth's orbit?

22. Consider the differentiated meteorites. We think the irons are from the cores, the stony-irons are from the interfaces between mantles and cores, and the stones are from the mantles of their differentiated parent bodies. If these parent bodies were like Earth, what fraction of the meteorites would you expect to consist of irons, stony-irons, and stones? Is this consistent with the observed numbers of each? (Hint: You will need to look up what percent of the volume of Earth is taken up by its core, mantle, and crust.)

23. Estimate the maximum height of the mountains on a hypothetical planet similar to Earth but with twice the surface gravity of our planet.