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**.

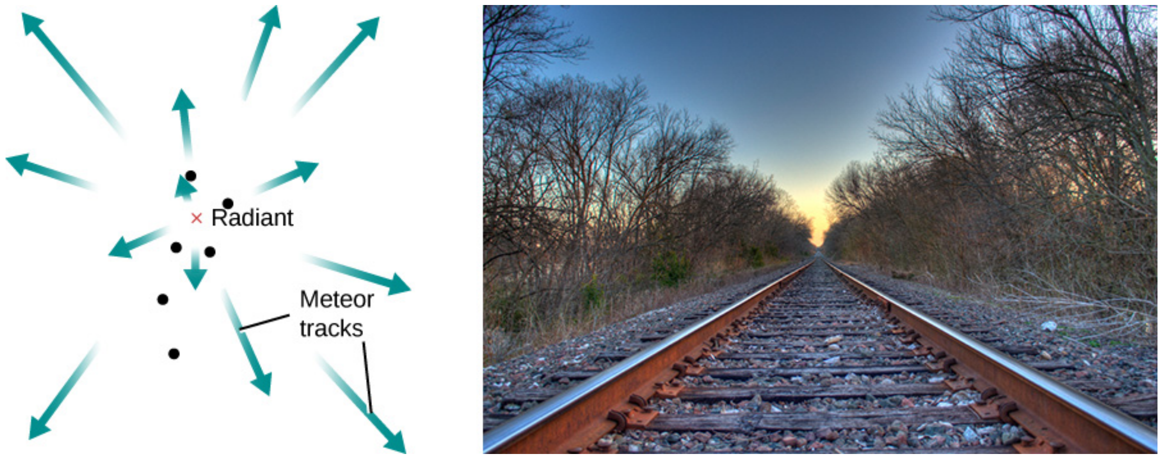


Figure 14.3 Radiant of a Meteor Shower. The tracks of the meteors diverge from a point in the distance, just as long, parallel railroad tracks appear to do. (credit "tracks": Nathan Vaughn)

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.

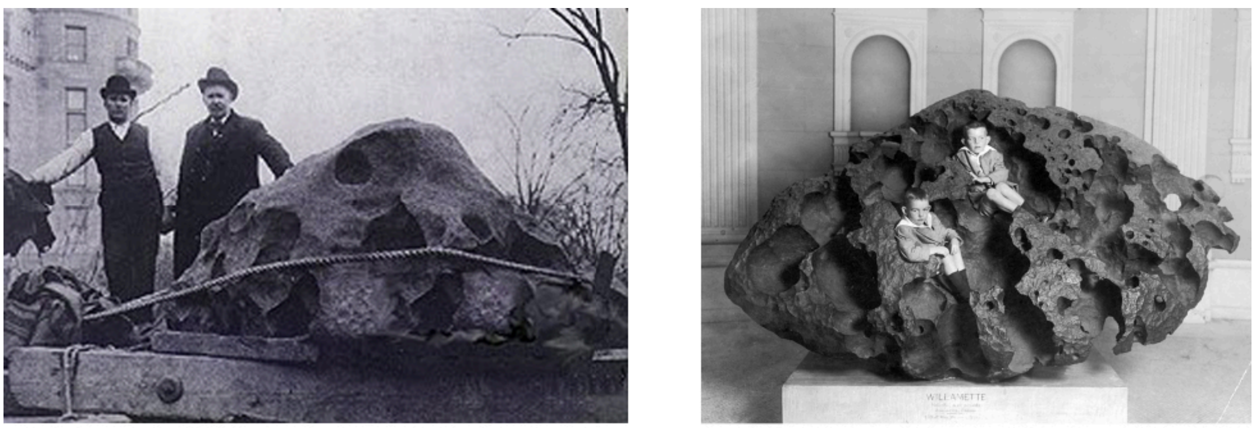
Meteorites sometimes fall in groups or showers. Such a fall occurs when a single larger object breaks up during its violent passage through the atmosphere. It is important to remember that such a *shower of meteorites* has nothing to do with a *meteor shower*. No meteorites have ever been recovered in 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.

(a) (b)

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**).

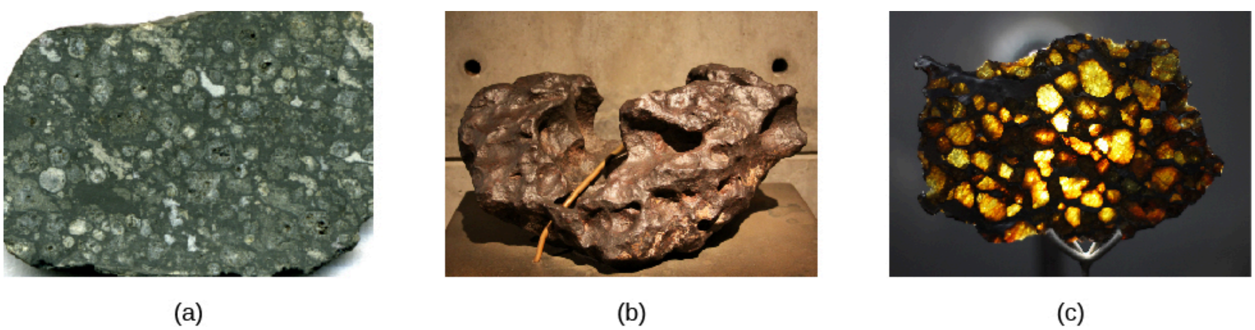


Figure 14.9 Meteorite Types. (a) This piece of the Allende carbonaceous meteorite has white inclusions that may date back to before the formation of the solar nebula. (b) This fragment is from the iron meteorite responsible for the formation of Meteor Crater in Arizona. (c) This piece of the Imilac stony-iron 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.

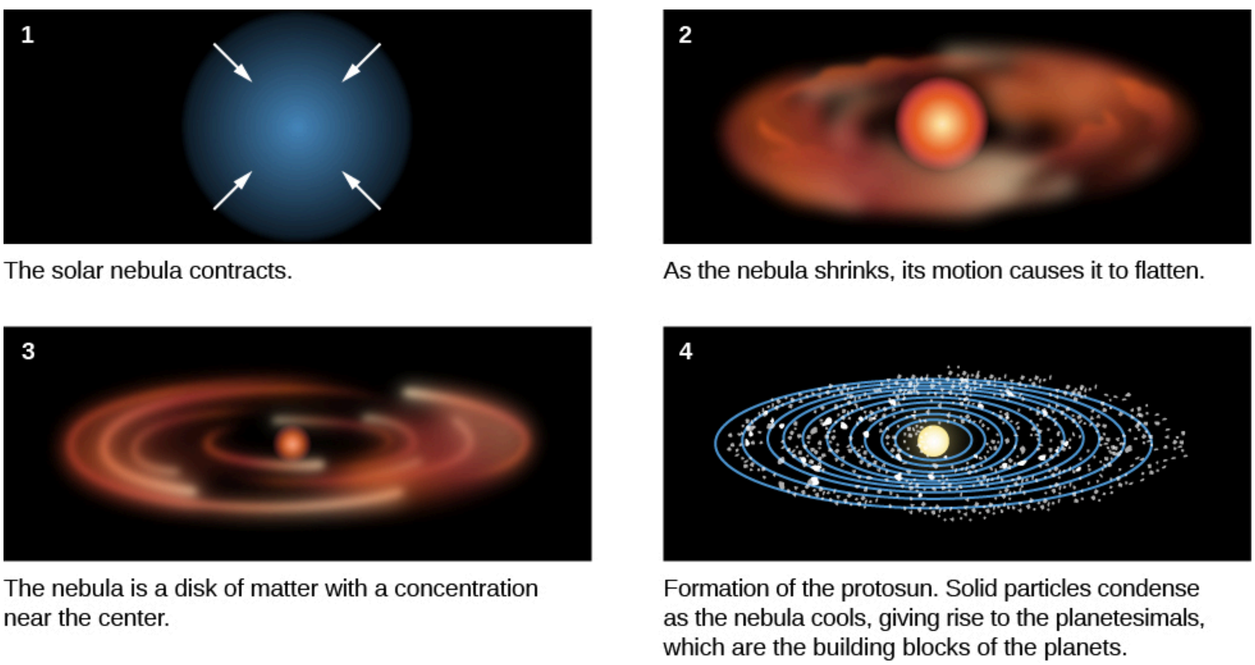


Figure 14.11 Steps in Forming the Solar System. This illustration shows the steps in the formation of the solar system from the solar nebula. As the nebula shrinks, its rotation causes it to flatten into a disk. Much of the material is concentrated in the hot center, which will ultimately become a star. 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.

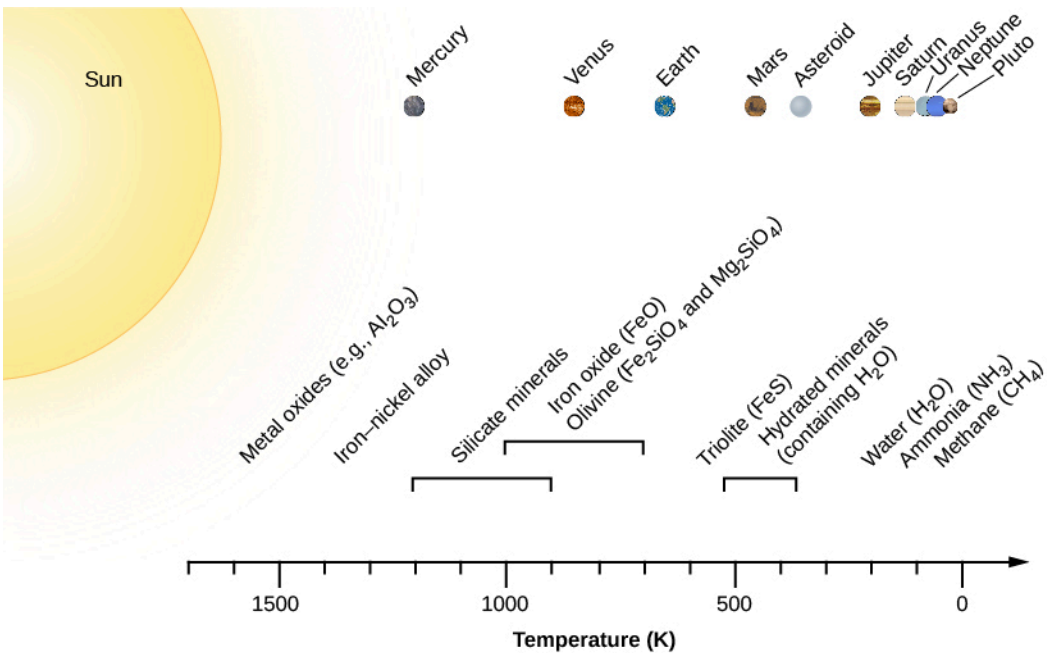


Figure 14.12 Chemical Condensation Sequence in the Solar Nebula. The scale along the bottom shows temperature; above are the materials that would condense out at each temperature under the conditions expected to prevail in the nebula.

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_{initial} = 10^6 yr and D_{initial} = 10^4 AU. Then, if D_{final} is in AU, P_{final} (in years) is given by $P_{\text{fina}} = 0.01 D_{\text{fina}}^2$. 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**).

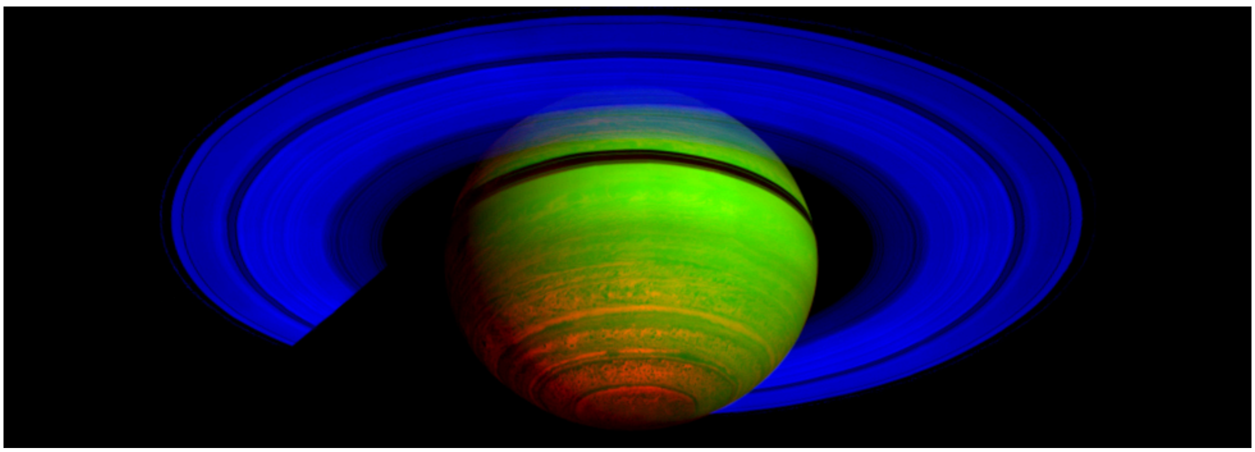


Figure 14.13 Saturn Seen in Infrared. This image from the Cassini spacecraft is stitched together from 65 individual observations. Sunlight reflected at a wavelength of 2 micrometers is shown as blue, sunlight reflected at 3 micrometers is shown as green, and heat radiated from Saturn's interior at 5 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.

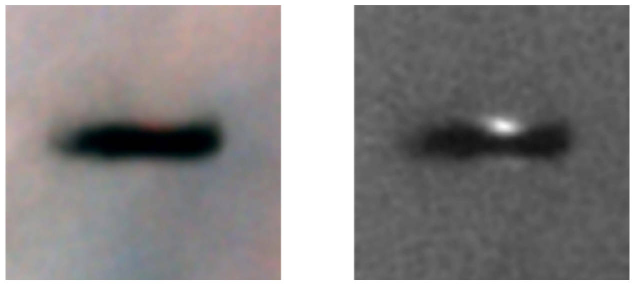
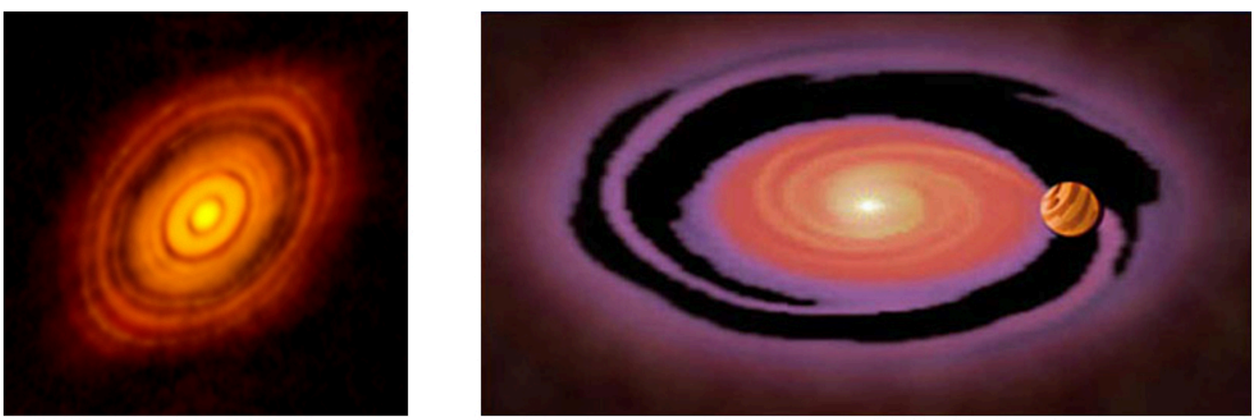


Figure 14.14 Protoplanetary Disk in the Orion Nebula. The Hubble Space Telescope imaged this protoplanetary disk in the Orion Nebula, a region of active star formation, using two different filters. The disk, about 17 times the size of our solar system, is in an edge-on orientation to us, and the newly 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.

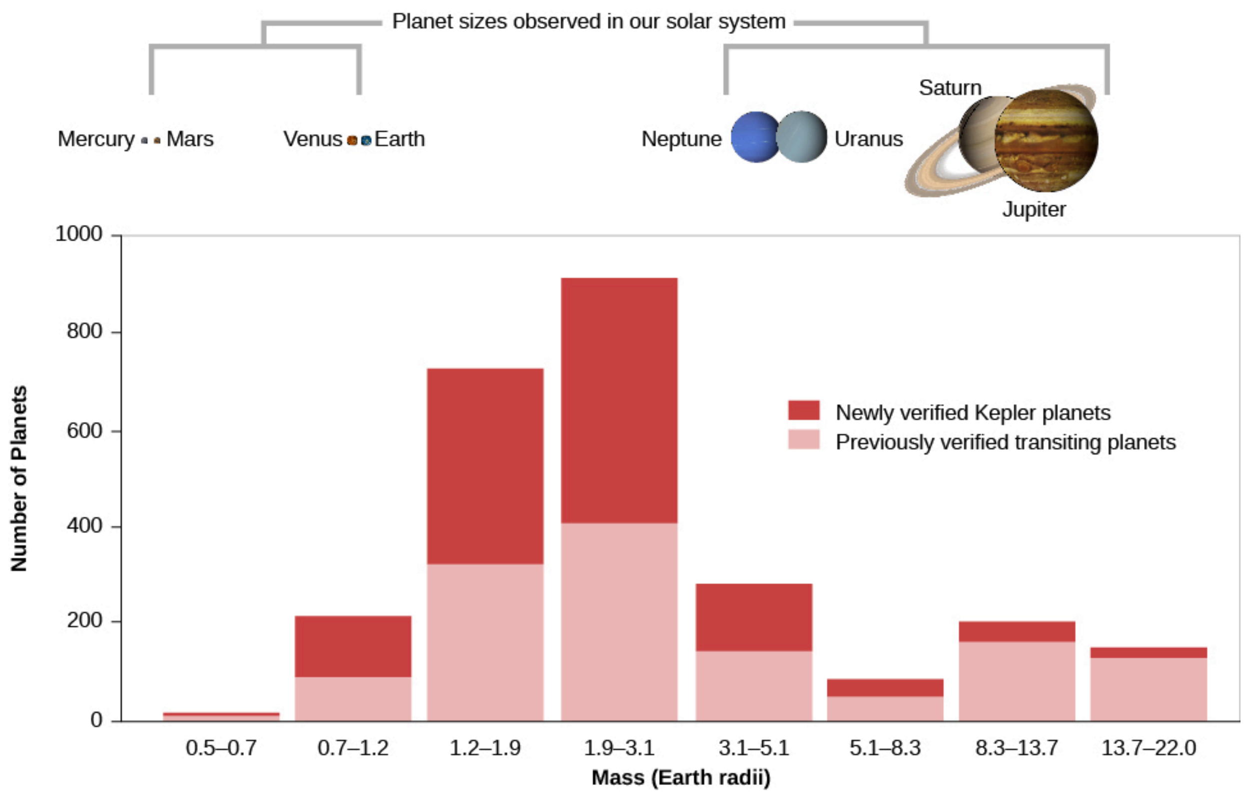


Figure 14.16 Transiting Planets by Size. This bar graph shows the planets found so far using the transit method (the vast majority found by the Kepler mission). The orange parts of each bar indicate the planets announced by the Kepler team in May 2016. Note that the largest number of planets found so 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.

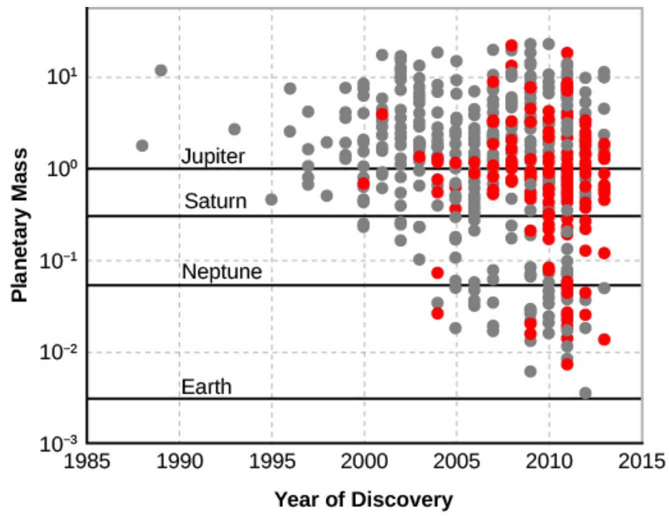


Figure 14.17 Masses of Exoplanets Discovered by Year. Horizontal lines are drawn to reference the masses of Jupiter, Saturn, Neptune, and Earth. The gray dots indicate planets discovered by measuring the radial velocity of the star, and the red dots are for planets that transit their stars. In the early 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.

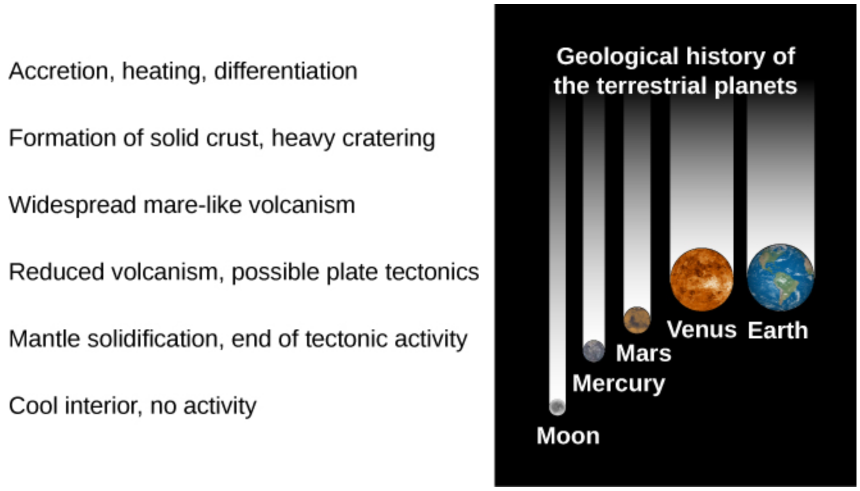


Figure 14.18 Stages in the Geological History of a Terrestrial Planet. In this image, time increases downward along the left side, where the stages are described. Each planet is shown roughly in its present stage. The smaller the planet, the more quickly it passes through these stages.

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.

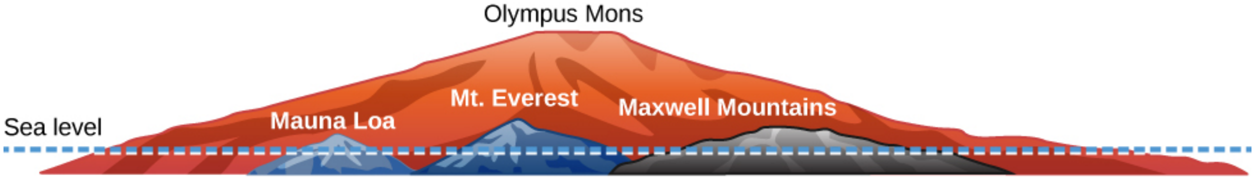


Figure 14.19 Highest Mountains on Mars, Venus, and Earth. Mountains can rise taller on Mars because Mars has less surface gravity and no moving plates. The vertical scale is exaggerated by a factor of three to make comparison easier. The label "sea level" refers only to Earth, of course, since the other 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.

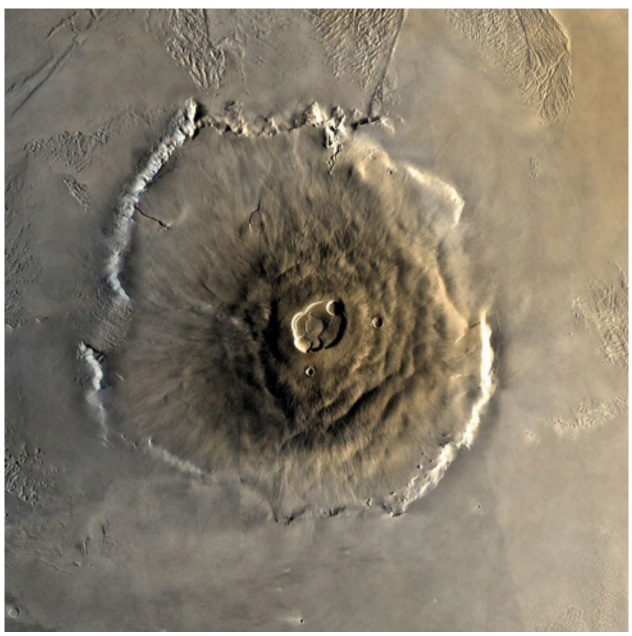


Figure 14.20 Olympus Mons. The largest martian volcano is seen from above in this spectacular composite image created from many Viking orbiter photographs. The volcano is nearly 500 kilometers wide at its base and more than 20 kilometers high. (Its height is almost three times the height of the tallest 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**).

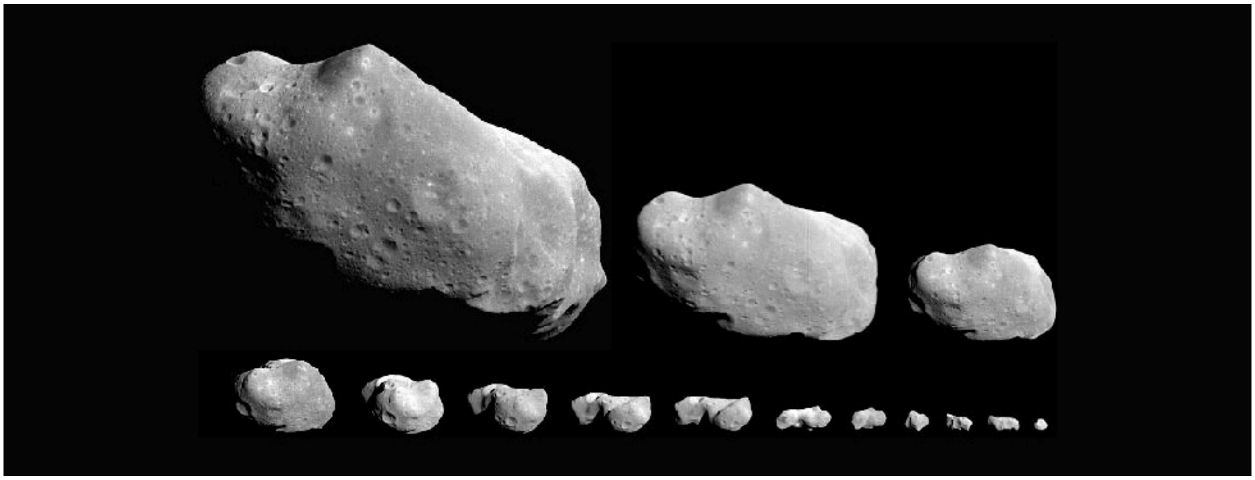


Figure 14.21 Irregular Asteroid. Small objects such as asteroid Ida (shown here in multiple views taken by the Galileo spacecraft camera as it flew past) are generally irregular or elongated; they do not have strong enough gravity to pull them into a spherical shape. Ida is about 60 kilometers long in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

Articles

Meteors and Meteorites

Alper, J. "It Came from Outer Space." *Astronomy* (November 2002): 36. On the analysis of organic materials in meteorites.

Beatty, J. "Catch a Fallen Star." *Sky & Telescope* (August 2009): 22. On the recovery of meteorites from an impact that was seen in the sky.

Durda, D. "The Chelyabinsk Super-Meteor." *Sky & Telescope* (June 2013): 24. A nice summary, with photos and eyewitness reporting.

Garcia, R., & Notkin, G. "Touching the Stars without Leaving Home." *Sky & Telescope* (October 2008): 32. Hunting and collecting meteorites.

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.