II ESSENTIALS FOR UNDERSTANDING THE SOLAR SYSTEM

IN THE CHAPTERS AHEAD YOU WILL DISCOVER

- how the solar system formed from a cloud of interstellar gas and dust (Essentials II)
- that the planets fall into groups with similar properties (Essentials II, Chapters 5, 6, 7)
- how astronomers characterize each planet's "personality" by its size, chemical composition, rotation rate, atmosphere, and features (Essentials II, Chapters 5, 6, 7)
- that the moons throughout the solar system are extremely varied (Chapters 5, 6, 7)
- that the solar system also contains debris—asteroids, meteoroids, and comets—left over from its formation (Chapter 8)
- why the Sun shines (Chapter 9)

THE PLANETS OF OUR SOLAR SYSTEM
This photomontage shows the Sun and the nine planets of our solar system. At the top (from left to right) are Mercury, Venus, Earth, and Mars. At the bottom (from left to right) are Jupiter, Saturn, Uranus, Neptune, and Pluto. (The images are not reproduced to the same scale. See Figure II-10 for a scale drawing.) (Calvin J. Hamilton)

R I V U X G

WHAT DO YOU THINK?

1. How many stars are there in the solar system?
2. Was the solar system created as a direct result of the formation of the universe?
3. How long has the Earth existed?
4. Is Pluto always the farthest planet from the Sun?
5. What typical shape(s) do moons have?

For as long as people have looked up at the heavens, they have wondered about the Sun, the Moon, and the planets visible to the naked eye. Telescopes revealed many new features of these objects, as well as the existence of other planets and moons, along with asteroids, meteoroids, and comets, all orbiting the Sun. The Sun and all the bodies that orbit it make up our **solar system.**

1 The solar system has only one star, the Sun. The stars you see in the night sky, plus billions of stars too far away to see with the naked eye, are members of a larger system called the *Milky Way Galaxy.* The solar system is also part of the Milky Way, a topic we discuss in Chapter 14.

Did the solar system form all at once, or did it come together by serendipity? How were its varied building blocks of rock, metal, ice, and gas created? How has the solar system changed since its formation, and what does its history tell us about the planets we see today? Within the past few decades, telescopes and space probes, along with the theories of modern science, have finally provided answers to these age-old questions. Our new wealth of information is giving us a rapidly growing understanding of our nearest neighbors in space.

II-1 The solar system formed from a cloud of cold gas and dust

Astronomers believe that the solar system formed from a vast cloud of interstellar gas and dust, called the **solar nebula.** This cloud condensed 4.6 billion years ago under the influence of its own gravitational force to form the planets, the Sun, and other bodies. We can determine where the matter comprising the solar nebula came from by examining the chemical elements found in the bodies of the solar system and in the stars.

By studying the spectra of stars and interstellar clouds, we know that hydrogen and helium are by far the most abundant elements in the universe. Together these elements account for 98% of the mass of all the material in existence—all the other elements combined account for only 2%. However, the Earth's mass contains less than 0.15% hydrogen and helium. Somehow the early solar system was enriched with the heavier elements we see today—oxygen, silicon, aluminum, iron, carbon, calcium, and others. Although these elements are rare in the universe as a whole, they are commonplace on Earth, and they are found to varying extents in all the other objects in the solar system. Our picture of the emerging solar nebula must explain these differences.

There is a good reason for the overwhelming abundance of hydrogen and helium throughout the universe. Most astronomers believe that the universe formed between 14 and 15 billion years ago with a violent event called the *Big Bang.* Only the lightest elements—hydrogen, helium, and a tiny amount of lithium—emerged when the cosmos was formed. The first stars, composed only of these three elements, condensed out of this primeval matter, probably within a few hundred million years after the Big Bang.

The difference in chemical composition between the early universe and the solar system shows that the solar system did not form as a *direct* result of the Big Bang. The solar system came billions of years later, and the heavier elements came to the solar nebula from stars that existed and exploded before the solar system formed. 2

Stars use various elements, such as hydrogen, helium, and carbon, to create energy. In this process, called *fusion,* lighter elements are transformed into heavier ones, such as hydrogen becoming helium or helium becoming carbon. We call fusion a *thermonuclear reaction* because the tremendous heat generated in the centers of stars is what enables nuclei of lighter elements there to combine, or fuse, into heavier elements. We explore details of the creation of this heavier matter in Chapters 11 and 12.

Near the ends of their lives, most stars cast matter out into space to form clouds of interstellar gas and dust. Often a star's outer layers are gradually expelled (Figure II-1a and b), but some stars end their lives with spectacular detonations called *supernovae* (Figure II-1c), which blow the stars apart. Either way, the space between the stars becomes filled with gas containing mostly hydrogen and helium—but now also enriched with heavy elements created in the stars. The solar nebula was a fragment of a large cloud of such gas and dust.

WEB LINK II.1

Sometimes, the explosive force of a supernova compresses fragments of interstellar gas and dust clouds that had been ejected from earlier generations of stars. These fragments are pulled inward on themselves by the mutual gravitational attraction of their gas and dust particles, thereby creating new star and planetary systems (Figure II-2). The collapsing matter is primarily hydrogen and helium, but the stars that ejected it had converted some of it to the other 90 naturally formed elements. These include the building blocks of life and this is believed to be how the solar system formed—the debris left over from a previous generation of stars. *We are made of star dust!*

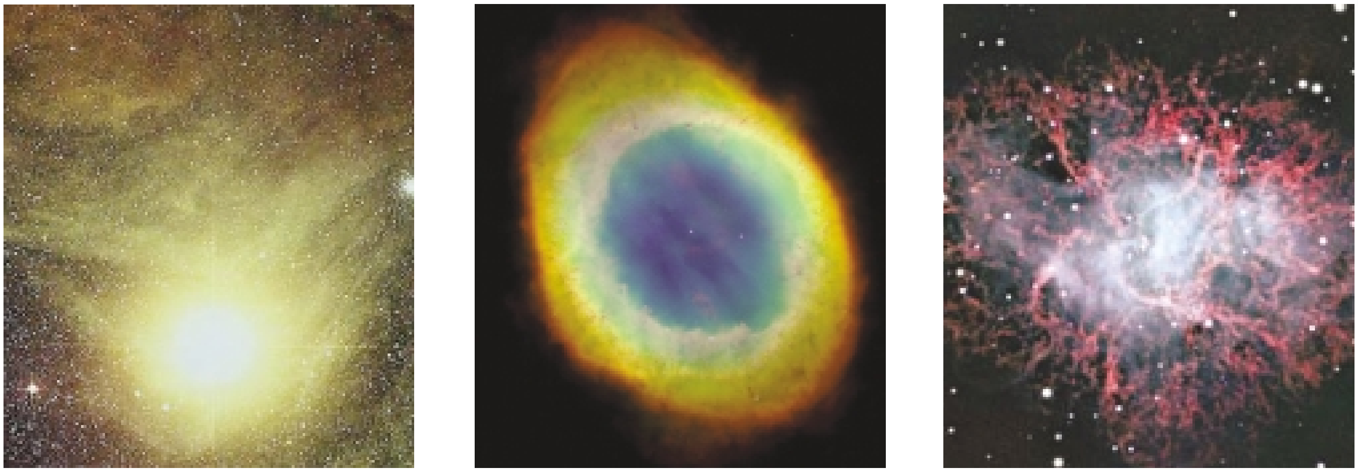


FIGURE II-1 How Stars Lose Mass (a) The brightest star in Scorpius, Antares, is nearing the end of its existence. Strong winds from its surface are expelling large quantities of gas and dust, creating this nebula reminiscent of an Impressionist painting. The scattering of starlight off this material makes it appear especially bright, even at a distance of 604 ly. (b) The Ring Nebula is just over 2000 ly from Earth. The central star shed its outer layers of gas and dust in an expanding spherical shell now about 1/2 ly across. The relatively gentle emission of this matter is called a planetary nebula, discussed in Chapter 12. (c) A supernova is the most powerful known mechanism for a star to shed mass. This is the Crab Nebula. Although it is about 6000 ly from Earth, it was visible during the day for three weeks during A.D. 1054. (a: David Malin/Anglo-Australian Observatory; b: NASA; c: Malin/Pasachoff/Caltech)

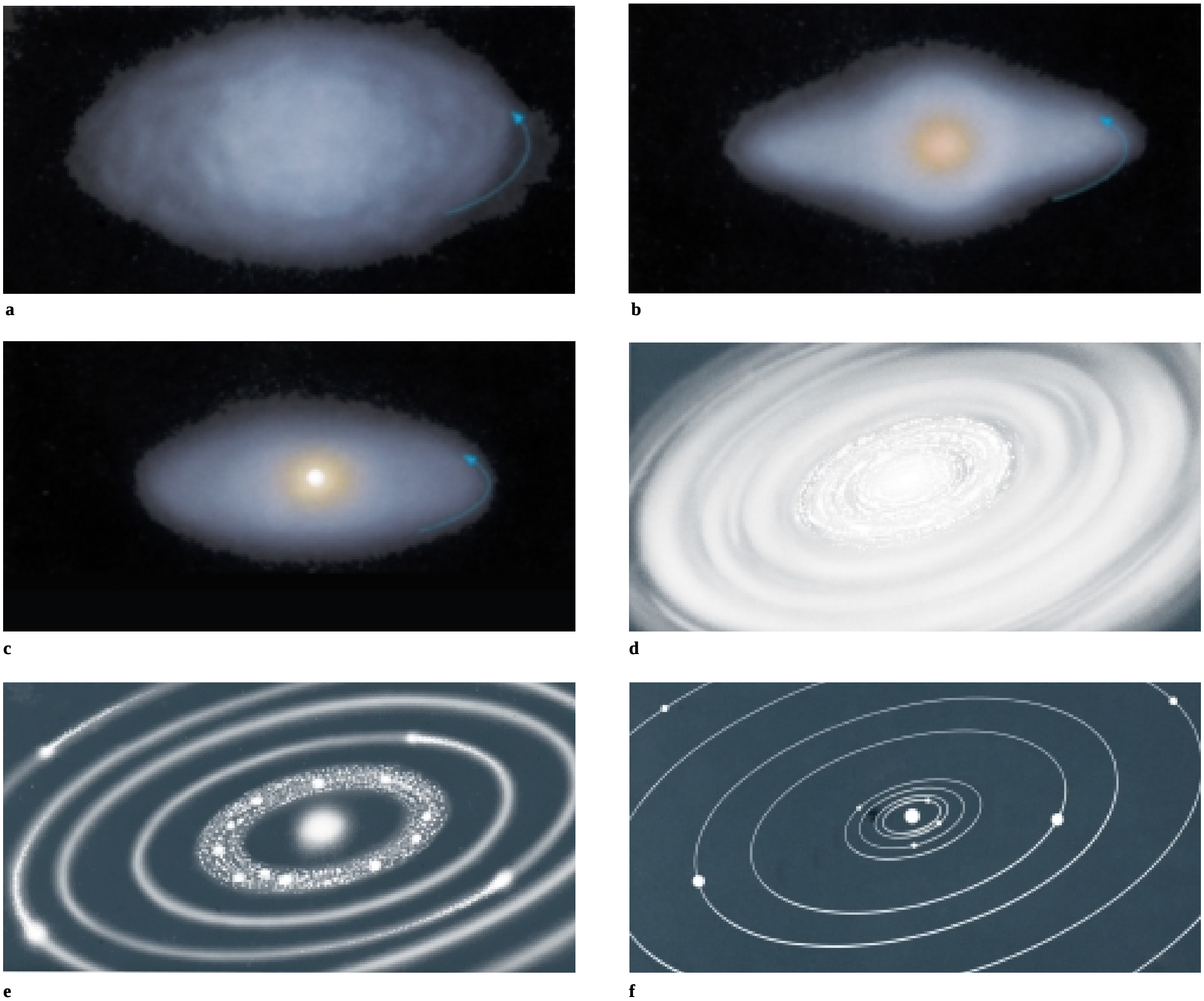
FIGURE II-2 A Dusty Region of Star Formation These young stars in the constellation Orion are still surrounded by much of the gas and dust from which they formed. The bluish, wispy nebulosity is caused by starlight reflecting off abundant interstellar dust grains. These grains are made of heavy elements (such as carbon, silicon, and iron) produced by earlier generations of stars. Astronomers hypothesize that the solar system formed from such a cloud of gas and dust. (©1980, 1984 Anglo-Australian Observatory)

II-2 Gravity and heat shaped the young solar system

To find out more about the solar system's origins, we look for clues in its pieces. Especially valuable is the interplanetary debris we know as asteroids, meteoroids, and comets. Some of these bodies are believed to be unchanged remnants from the formation of the solar system. Other clues to the origin of our solar system have recently been found in distant stars, where planetary systems like our own are developing.

Initially, it was very cold inside the solar nebula—well below the freezing point of water. The nebula began with a diameter of at least 100 AU and a total mass about 2 to 3 times the mass of the Sun. Ice and ice-coated dust grains composed of heavy elements were scattered abundantly across this vast volume. Hydrogen and helium gas, accompanied by this ice and dust, fell toward the center of the solar nebula under the influence of the gravitational attraction of other gas in the nebula. As a result, the density and pressure at the center of the nebula began to increase, producing a concentration of matter called the **protosun.**

As the nebula continued to contract, atoms at its center collided with one another with increasing speed and frequency. Such collisions created heat, causing the temperature deep inside the solar nebula to soar. Therefore, the first heat in the solar system came from colliding gas, not from fusion, which began later.



ANIMATION II.1

FIGURE II-3 The Formation of the Solar System This sequence of drawings shows six stages in the formation of the solar system. (a) A slowly rotating cloud of interstellar gas and dust begins to contract because of its own gravity. (b) A central condensation, the protosun, forms as the cloud flattens and rotates faster. (c) A flattened disk of gas and dust surrounds the protosun, which has begun to shine. (d) The Sun's rising temperature removes the gas from the inner regions, leaving dust and larger debris revolving in place. (e) The planets have established dominance in their regions of the solar system. (f) The solar system as it appears today.

The planets and other bodies orbiting the protosun formed because the solar nebula was swirling (rotating). As a result of this rotation, the nebula had angular momentum (see An Astronomer's Toolbox 2-1). Conservation of angular momentum prevented some of the nebula from falling inward. Without this initial rotation, everything in the solar nebula would have fallen straight into the protosun, leaving no matter behind to form the planets. Mathematical studies show that the combined effects of gravity and rotation transform even an irregular cloud fragment (which the solar nebula probably was) into a rotating disk with a warm center and cold edges, as shown in Figure II-3. The disk shape explains why the orbits of the planets are all nearly in the same plane.

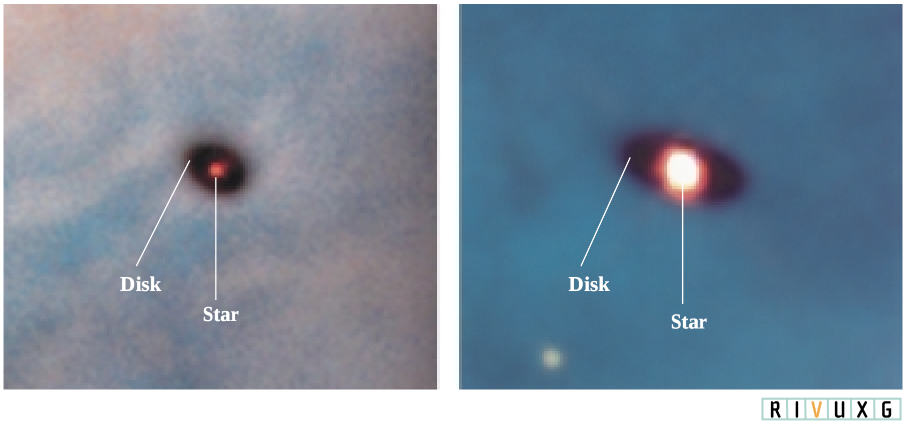



FIGURE II-4 Young Circumstellar Disks of Matter These Hubble Space Telescope images show circumstellar disks surrounding two stars 1500 light-years away from Earth in the Orion Nebula. These stars, both less than 10 million years old, are believed to be surrounded by protoplanetary gas and dust. (STScI, M. J. McCaughrean/MPIA, C. R. O'Dell/ Rice University, NASA)

While we cannot see our solar system as it was back then, astronomers have found disks of gas and dust surrounding other young stars, like those shown in Figure II-4. Called **protoplanetary disks** or **proplyds,** these systems are believed to be undergoing the same initial stage of evolution that we are describing here for our solar system.

Temperatures around the young protosun soon began to climb. The rising temperatures vaporized all the common icy substances in the inner region of the solar nebula and pushed light gases like hydrogen and helium outward. In this inner region, where the Earth orbits today, mostly heavier elements remained. These heavy elements were eventually to come together and form the four inner planets: Mercury, Venus, Earth, and Mars.

II-3 Collisions in the early solar system led to the formation of planets

The formation of the inner planets was the result of innumerable impacts of small, rocky particles in the solar system's protoplanetary disk. Initially, neighboring dust grains (Figure II-5) and pebbles in the solar nebula collided and stuck together. Then, over a period of a few million years, these accumulations of dust and pebbles coalesced into larger objects called **planetesimals,** with diameters of about 10 km.

During the next stage, the planetesimals collided. Because of their mutual gravitational attraction, they coalesced into still larger objects called **protoplanets.** This accumulation of material is called **accretion.** Computer simulations of the inner solar system based on Newton's laws (see Section 2-5) suggest that accretion continues for roughly 100 million years and should lead to the formation of fewer than half a dozen planets (Figure II-6). The agreement between predictions of the number of planets and the number in our inner solar system is encouraging. However, observations indicate that the planets form more quickly.


MORE TO KNOW II-1 Computer Simulations

Insight into Science **Computer Aid Analysis** Many equations are so complex that they require computer analysis to enable us to understand their implications. An example is the physics of the formation of the planets and the Sun. Observations then lead to refined computer models.

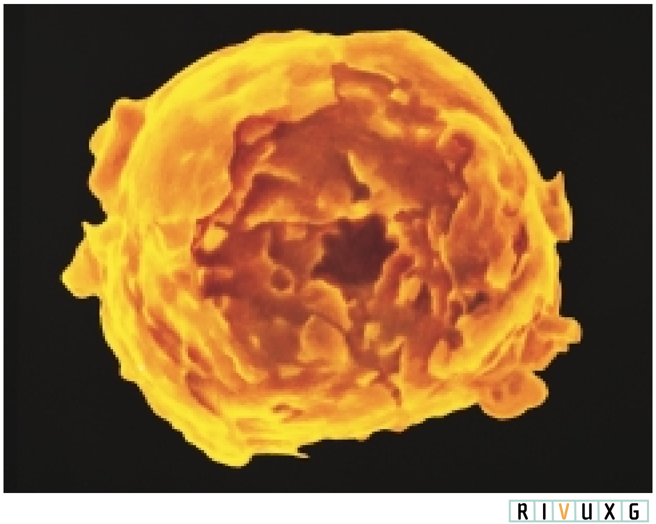


FIGURE II-5 Space Dust Collected by a high-flying aircraft, this piece of interplanetary dust is believed to be typical of the state of matter in the protoplanetary disk. It is about 20 μ (0.02 mm) across. Such particles stuck together to form larger and larger chunks of matter, eventually creating such objects as the planets, moons, and asteroids. (Scott Messenger/University of Washington, St. Louis/Science Photo Library/Photo Researchers)

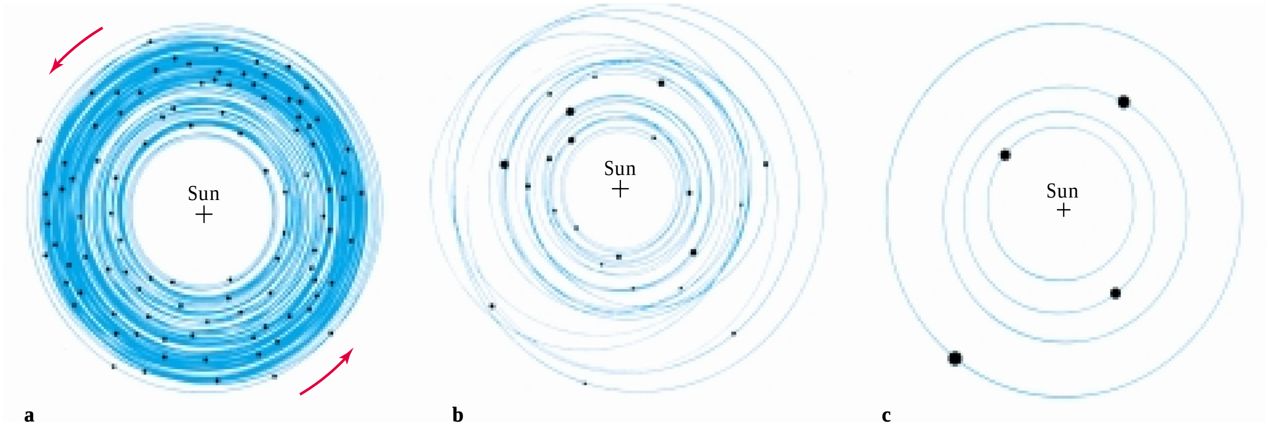


FIGURE II-6 Accretion of the Inner Planets These three drawings show the results of a computer simulation of the formation of the inner planets. (a) The simulation begins with 100 planetesimals. (b) After 30 million years, these planetesimals have coalesced into 22 protoplanets. (c) This final view is for an elapsed time of 441 million years, but the formation of the inner planets in this simulation is almost complete after only 100 million years.

While the inner regions of the solar system were heating up, temperatures in the outer regions of the solar nebula remained quite cool. Ice and ice-coated dust, along with hydrogen and helium gas, were able to survive in these cooler regions. The large outer planets—Jupiter, Saturn, Uranus, and Neptune—also probably formed from the accretion of planetesimals. For each, a rocky core even bigger than the Earth apparently served as a "seed," and for about a million years the core became coated with additional rock and gas. When the gas-rich envelope became as massive as the rocky core, the gas began to accumulate at a runaway pace. Thereafter, the envelope pulled in all the gas in its vicinity, creating a huge hydrogen-rich shell surrounding a core of rocky material.

Because of their gaseous shells, the outer planets today include abundant quantities of hydrogen, helium, methane, ammonia, and water. Many of the moons of the outer planets are also partially composed of these low-density substances.

During the millions of years that the planets were forming, so, too, was the Sun. During this time the temperature and pressure at the center of the contracting protosun continued to climb. Finally, the center of the protosun became hot enough to ignite thermonuclear reactions. Now, hydrogen fused into helium in its core, thereby releasing huge amounts of energy, and the Sun was born. Sunlike stars take approximately 100 million years to form from a nebula and settle down, which means that the Sun became a full-fledged star at about the same time as the accretion of the inner planets was being completed. Indeed, radiation from the Sun prevented new planetesimal formation, thereby limiting the sizes of the planets.

According to radioactive dating of the oldest debris ever
discovered from space, the solar system was roughly in the 3
form we know today just under 4.6 billion years ago. While the planets were in place, only a few of the dozens of moons were in orbit, and innumerable pieces of rocky and icy debris were on collision courses with the planets. Indeed, evidence indicates that our Moon was created by such a collision (see Chapter 5).

Once formed, our Moon's surface was scarred by numerous impacts (Figure II-7).These scars, called **craters,** are also found on those planets and moons that do not have appreciable atmospheres or geological activity that would otherwise erase these features. Indeed, the Moon's virtually airless environment has preserved important information about the early history of the solar system. (Note that we capitalize the word *moon* only when we are referring to the Earth's Moon.)

Radioactive dating (see An Astronomer's Toolbox 4-2) of Moon rocks brought back by the Apollo astronauts indicates that the rate of impacts declined dramatically about 3.8 billion years ago. Since that time, impact cratering has proceeded at a very low rate. Thus, most of the craters on the Moon and planets were formed during the first 800 million years of the solar system's history, as the young planets swept up rocky debris left over from the solar nebula. Conditions developed on the young Earth, especially the presence of liquid water, so that biological evolution could begin to eventually occur here. There is growing evidence that liquid water existed on Mars and may still exist inside it and inside Jupiter's moon Europa, raising the hotly debated question of whether simple life evolved on those worlds, too.

FIGURE II-7 Our Moon This photograph, taken by astronauts in 1972, shows thousands of the craters produced by impacts of rocky debris left over from the formation of the solar system. Age-dating of lunar rocks brought back by the astronauts indicates that the Moon is about 4.5 billion years old. Most of the lunar craters were formed during the Moon's first 700 million years of existence, when the rate of bombardment was much greater than it is now. (NASA)

II-4 Comparisons among the nine planets show distinct similarities and significant differences

The nine planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. As shown in Figure II-8, the orbits of the four inner planets—Mercury, Venus, Earth, and Mars—are crowded close to the Sun. In contrast, the orbits of the four large outer planets—Jupiter, Saturn, Uranus, and Neptune—are widely spaced at greater distances from the Sun. Pluto usually orbits at the far fringes of the part of the solar system inhabited by planets.

Kepler's laws (see Chapter 2) showed us that all the planets have elliptical orbits. Even so, most of their orbits are 4
nearly circular. The exceptions are Mercury and Pluto, whose orbits are noticeably elliptical. In fact, Pluto's orbit sometimes takes it nearer to the Sun than its neighbor, Neptune. In 1979, Pluto passed inside Neptune's orbit. Neptune was the most distant planet from the Sun until February 1999, when Pluto's elliptical orbit once again took it farther out than Neptune (Figure II-9). Pluto will be farther from the Sun than Neptune for about the next 230 years.

All the planetary orbits except that of Pluto lie in planes close to the ecliptic. Pluto's orbit has a conspicuous tilt (called an *orbital inclination*) compared with the orbits of

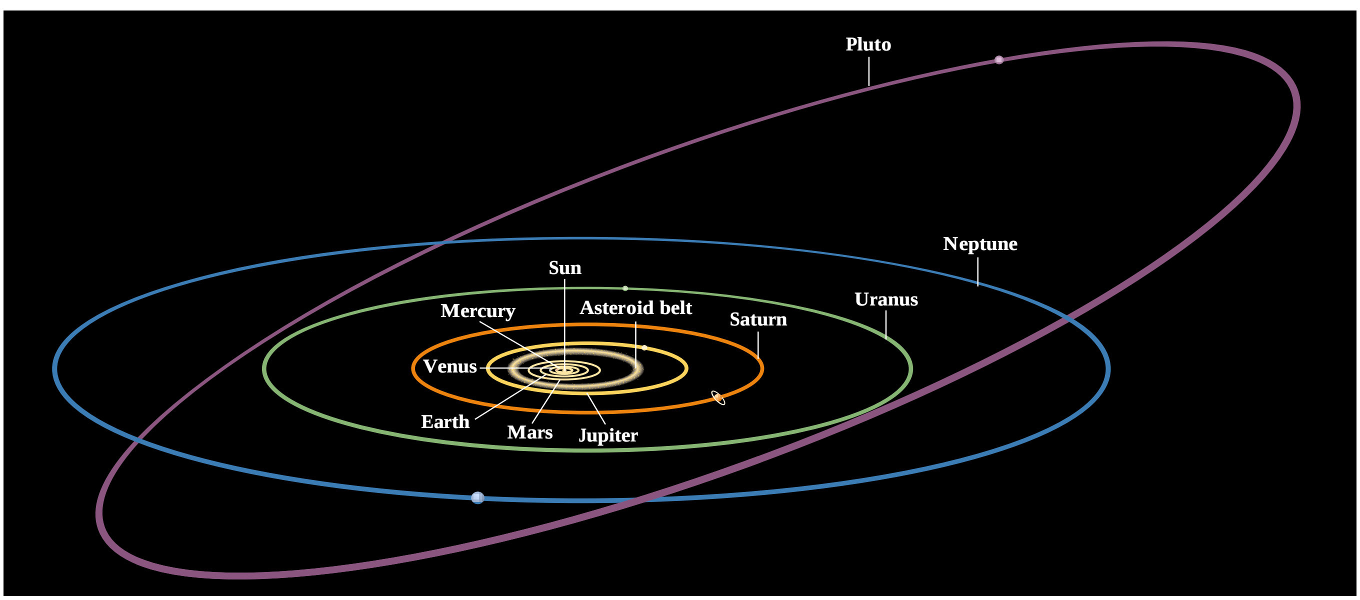


FIGURE II-8 The Solar System This scale drawing shows the distribution of planetary orbits around the Sun. The four inner planets are located close to the Sun; the five outer planets orbit at much greater distances from the Sun. The viewpoint of this figure makes the orbits appear much more oval-shaped than they really are. Seen from above the disk of the solar system, most of the orbits appear nearly circular, as shown for Neptune in Figure II-9. All orbits are counterclockwise because the view is from above the Earth's north pole.

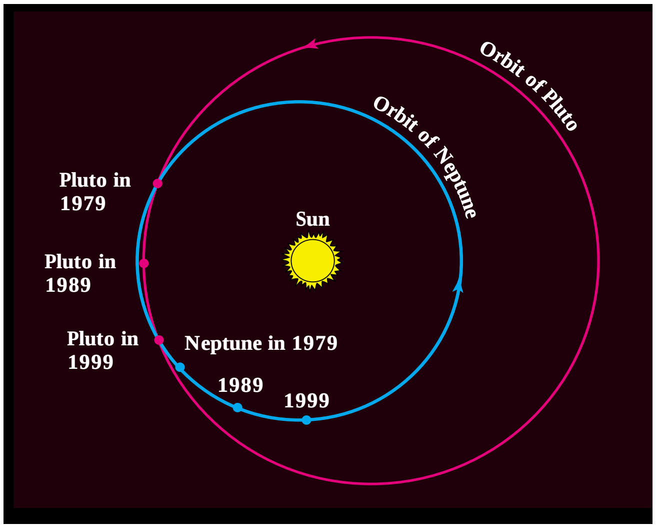


FIGURE II-9 Pluto's Orbit Is Highly Elliptical Pluto has the most elliptical orbit of any planet. Indeed, it spends part of the time closer to the Sun than to Neptune. It last moved inside Neptune's orbit in 1979 and moved back outside in 1999. Note that Pluto and Neptune will never collide because their orbits are synchronized by their gravitational interaction to keep them apart.

TABLE II-1 Orbital Characteristics of the Planets

	Average distance from Sun (AU)	Average distance from Sun (10^6 km)	Orbital period (yr)
Mercury	0.39	58	0.24
Venus	0.72	108	0.62
Earth	1.00	150	1.00
Mars	1.52	228	1.88
Jupiter	5.20	778	11.86
Saturn	9.54	1427	29.46
Uranus	19.19	2871	84.01
Neptune	30.06	4497	164.79
Pluto	39.53	5914	248.54

the other planets (see Figure II-8). Table II-1 lists some orbital characteristics of the nine planets.

Size is the most obvious physical difference among the planets. The smallest of the four giant outer planets, Neptune, is nearly 4 times larger in diameter than the Earth, the largest of the four inner planets. First place among the giant planets goes to Jupiter, whose diameter is about 11 times bigger than that of Earth. Pluto is the smallest of all the planets, and is even smaller than the seven largest moons, including our own. Figure II-10 shows the Sun and the planets drawn to the same scale. The diameters of the planets are given in Table II-2.

Mass is another characteristic that distinguishes the inner and outer planets. The four inner planets have low masses compared with the giant planets. Again, first place goes to Jupiter, whose mass is 318 times greater than Earth's (see Table II-2).

Size and mass can be combined in a useful way to provide information about the chemical composition of a planet (or any other object, for that matter). Matter composed of heavy elements, like iron or lead, has more particles compressed into the same volume than matter composed of light elements, like hydrogen, helium, or carbon. Therefore, objects composed primarily of heavier elements have a greater **average density** than objects composed primarily of lighter elements. Average density is given by the equation

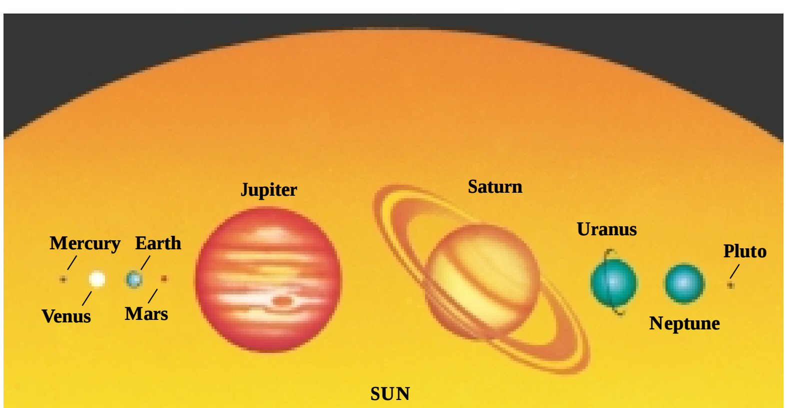


FIGURE II-10 The Sun and the Planets This drawing shows the nine planets in front of the disk of the Sun, with all ten bodies drawn to the same scale. The four planets orbiting nearest the Sun (Mercury, Venus, Earth, and Mars) are small and made of rock and metal. The next two planets (Jupiter and Saturn) are large and composed primarily of hydrogen and helium. Uranus and Neptune are also large but contain much water, as well. Pluto has roughly equal amounts of rock and ice.

TABLE II-2 Physical Characteristics of the Planets

	Diameter (km)	Diameter (Earth = 1)	Mass (kg)	Mass (Earth = 1)	Average density (kg/m^3)
Mercury	4,878	0.38	3.3×10^{23}	0.06	5430
Venus	12,100	0.95	4.9×10^{24}	0.81	5250
Earth	12,756	1.00	6.0×10^{24}	1.00	5520
Mars	6,786	0.53	6.4×10^{23}	0.11	3950
Jupiter	142,984	11.21	1.9×10^{27}	317.94	1330
Saturn	120,536	9.45	5.7×10^{26}	95.18	690
Uranus	51,118	4.01	8.7×10^{25}	14.53	1290
Neptune	49,528	3.88	1.0×10^{26}	17.14	1640
Pluto	2,300	0.18	1.3×10^{22}	0.002	2030

$$\text{Average density} = \frac{\text{total mass}}{\text{total volume}}$$

The chemical composition (kinds of elements) of any object therefore determines how much space the object occupies per unit mass. For example, a kilogram of iron takes up less space (is denser) than a kilogram of water, even though both have the same mass. Average density is expressed in kilograms per cubic meter. To help us grasp this concept, we compare the average densities of the planets to something familiar, namely water, which has an average density of 1000 kg/m^3.

The four inner planets have high average densities compared to water (see Table II-2). In particular, the average density of the Earth is 5520 kg/m^3. Because the density of typical surface rock is only about 3000 kg/m^3, the Earth must contain a large amount of material inside it that is denser than surface rock.

In sharp contrast, the outer planets have relatively low average densities. For example, Saturn has an average density less than that of water. Their low densities support the belief that the giant outer planets contain significant amounts of the light elements hydrogen and helium.

Pluto again is an oddity. Although it is smaller than any of the inner planets, its average density falls between those of the Earthlike and the giant outer planets. Pluto is probably composed of a mixture of rock and ice, because its average density is between that of rock and ice.

Further information about the chemical composition of bodies in the solar system (among other places) can be obtained from their spectra. For solar system objects, this radiation is primarily sunlight scattered off the surface or clouds surrounding each object. As we saw in Chapter 4, the spectra provide us with details of an object's chemical composition. Spectra, for example, tell us about the chemical composition of atmospheres in the solar system.

More to Know II-2 Spectra

Insight into Science **Astronomical Measurement**
The laws of physics allow us to infer things we cannot measure directly. For example, we derive information about the chemical compositions of planets from their masses and volumes. Kepler's laws yield the mass of each planet from the periods of their moons' orbits, while the measured diameters of the planets yield their volumes. As shown in the equation above, dividing mass by volume yields the average density, which tells us about their chemistries.

The planets can be placed roughly into four groups. The four inner planets form the first group, followed by Jupiter and Saturn as the second, Uranus and Neptune as the third, and Pluto as the fourth. A group of one? In fact, Pluto actually appears to be the largest of myriad small, distant bodies in the solar system called *Kuiper belt objects*. Indeed, at least 485 such bodies orbiting the Sun beyond Pluto have been identified, as we will discuss in Chapter 8.

From photographs, spectra, and average densities, we can draw conclusions about the compositions of all the planets.

The four inner ones, composed primarily of rock and metal, are called **terrestrial planets** because they resemble the Earth (in Latin, *terra*). Mountains, craters, canyons, and volcanoes are common on their hard, rocky surfaces.

Jupiter and Saturn are composed primarily of hydrogen and helium. Uranus and Neptune have extremely large quantities of water as well as much hydrogen and helium, and as noted above, Pluto is probably a mix of rock and ice. Clouds enshroud Jupiter, Saturn, Uranus, and Neptune. These four were traditionally called the *Jovian planets* (the Roman god Jupiter was also called Jove). However, this single grouping hides significant differences in the sizes and chemistries of Jupiter and Saturn, on the one hand, and Uranus and Neptune on the other, so we will explore them as two groups in Chapter 7. The montage of photographs that opens this section shows the distinctive appearances of the planets.

The different surfaces (or the upper cloud layers) of the planets reflect different amounts of light back out into space. The fraction of incoming light returning directly into space is given by each body's **albedo.** An object that reflects no light has an albedo of 0.0; for example, powdered charcoal has an albedo of nearly 0.0. An object that reflects all the light incident upon it (a high-quality mirror comes close) has an albedo of 1.0. The albedo multiplied by 100 gives the percentage of light directly scattered off that body. The three inner planets with solid surfaces exposed to space (Mercury, Earth, and Mars) have albedos of 0.37 or less. The five planets surrounded by clouds have albedos of 0.47 or more. While Pluto's albedo of 0.5 is relatively high, we do not yet know much about its surface.

WEB LINK II.3

5 Every planet except Mercury and Venus has moons (sometimes called *natural satellites*). There are at least 88 moons in the solar system, and more are still being discovered. Unlike our Moon, most moons are irregularly shaped, more like potatoes than spheres. We will discover that there is as much variety among moons as there is among planets.

II-5 Minor debris from the formation of the solar system still exists

In addition to the nine planets and their moons, many other objects orbit the Sun. Between the orbits of Mars and Jupiter are believed to be millions of such bodies, called **asteroids,** most of them smaller than a kilometer across. This region is called the **asteroid belt.** Asteroids are composed primarily of metal and rock. The largest asteroid, Ceres, has a diameter of about 900 km. The next largest, Pallas and Vesta, are each about 500 km in diameter. Still smaller ones are increasingly numerous. There are many thousands of kilometer-sized asteroids. A close-up picture of the asteroid Gaspra is shown in Figure II-11. In addition to the asteroids between Mars and Jupiter, other asteroids have highly elliptical orbits that take them across the paths of some of the planets. Some asteroids have their own moons, such as asteroid Ida, which is orbited by heavily cratered Dactyl.

R I V U X G

WEB LINK II.4

FIGURE II-11 An Asteroid This picture of the asteroid Gaspra was taken in 1991 by the Galileo spacecraft on its way to Jupiter. The asteroid measures $12 \times 20 \times 11$ km. Millions of similar chunks of rock orbit the Sun between the orbits of Mars and Jupiter. (NASA)

VIDEO II.1 WEB LINK II.5

Pieces of rocky and metallic debris even smaller than asteroids are called **meteoroids.** Typical meteoroids are boulder-sized or smaller and apparently exist throughout the disk of the solar system, although most are in the asteroid belt. Chemical studies show that many meteoroids are small fragments of asteroids that broke off when larger bodies collided.

WEB LINK II.6

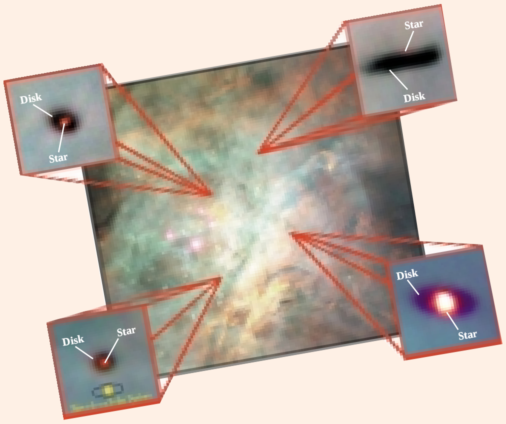
Quite far from the Sun, beyond the orbit of Pluto, are hundreds of billions of chunks of ice called **comets.** Some comets orbit in a doughnut-shaped region centered on the ecliptic, the Kuiper belt, while others are believed to be distributed in a sphere around the Sun. Many comets have highly elongated orbits that occasionally bring them close to the Sun. When this happens, the Sun's radiation vaporizes some of the comet's ices, producing long, flowing tails (Figure II-12).

Icy debris is also believed to have been observed orbiting other stars. Studying this material is one method astronomers use in their quest to locate planets outside the solar system.

GUIDED DISCOVERY The Formation of the Solar System

4.7 billion years ago

- Solar nebula begins collapsing.
- Protosun starts growing from in-falling gas.



4.6 billion years ago

- Disk of matter forms around the young protosun.
- As regions of the disk clump and collide, planets begin to form.

4.51 billion years ago

- Formation of meteoroids, asteroids, comets, and planets essentially complete.
- Sun starts nuclear fusion and brightens.
- Sun's energy causes remaining gas and dust to dissipate into interstellar space.
- Meteoroids, asteroids, and comets continue to strike planets and the Sun.

3.1 billion years ago

- Most planetesimals have become parts of planets or the Sun.
- Frequent major impacts end.

R I V U X G

FIGURE II-12 A Comet The solid part of a typical comet is an irregularly shaped chunk of ice and rocky debris 10 km in diameter. When a comet passes near the Sun, solar radiation vaporizes some of the comet's ices, and the resulting gases and dust form one or two tails millions of kilometers long. This photograph shows Comet Kohoutek in 1974. (NASA)

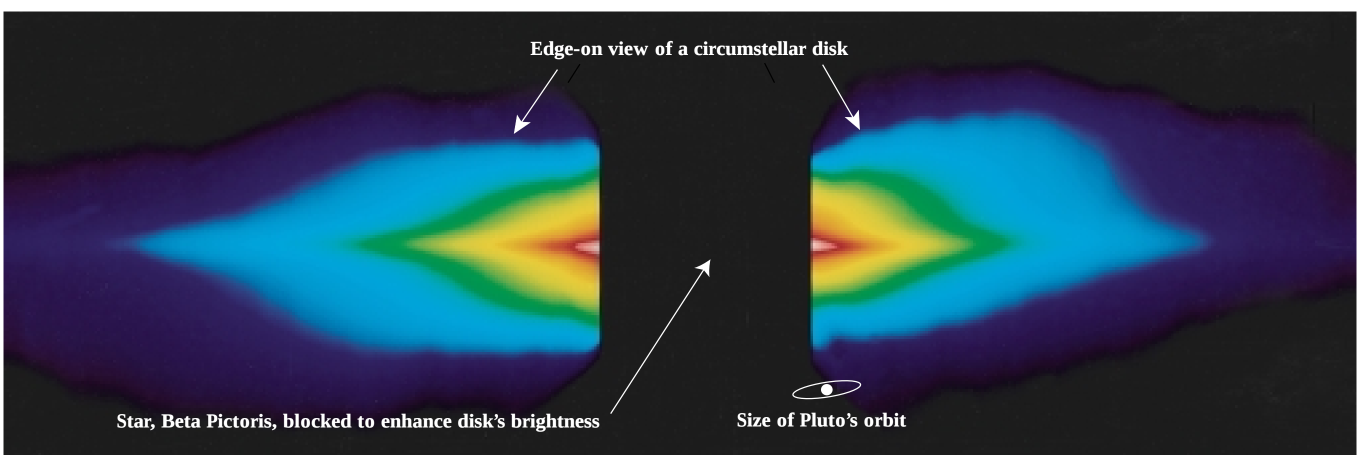
II-6 Planets orbiting other stars have been discovered

Astronomers are discovering planets outside our solar system around an ever-growing number of stars. More than 80 such planets have been located. These discoveries began with visual images showing disks of material orbiting a few stars, such as Beta Pictoris. The disk around Beta Pictoris is warped, a sign that planets may exist there as well. The planets would tug on different areas of the disk differently, thereby creating the warp (Figure II-13). This star and the material orbiting it formed only 20 million years ago. In 2001, astronomers also detected evidence that millions of comets have formed in this system. By studying such systems as Beta Pictoris, we hope to better understand the formation of the solar system, including addressing the question of whether the Earth acquired its water from comets in the solar system.

WEB LINK II.7

Planets outside the solar system are called *extrasolar planets*. Observing them in orbit around other stars is challenging, because even high-albedo planets reflect less than a millionth as much light as a star emits. So far, extrasolar planets have been too dim or too close to their parent stars to be seen easily. Hence, scientists look for planets by indirect observation, primarily by detecting their gravitational tugs on the stars they orbit.

Some planets are discovered by measuring the radial velocity (defined in Chapter 4) of their stars, as measured by the Doppler shifts of the stars' spectra. This motion toward or away from Earth is created by the gravitational pull of the



R I V U X G

FIGURE II-13 A Circumstellar Disk of Matter This photograph shows a disk of material orbiting the star Beta Pictoris (blocked out in this image) 50 ly from Earth. Twenty million years old, this disk is believed to be composed primarily of iceberglike bodies orbiting the star. Notice that the edge-on disk is warped. This is believed to be due to the gravitational tug of at least one planet orbiting Beta Pictoris inside the inner edge of the disk (in the central region that is blocked out). (STScI, A. Schultz/CSC/STScI and NASA)

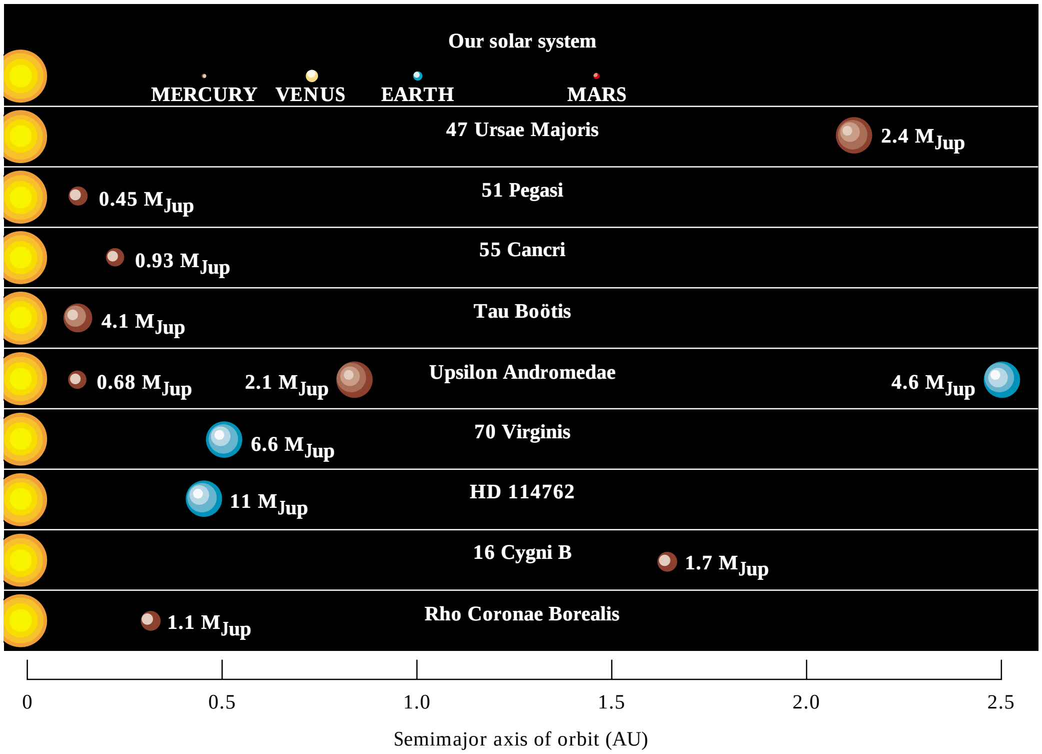


FIGURE II-14 Planets Around Normal Stars This figure shows the separation between extrasolar planets and nine Sunlike stars. The corresponding star names are given in the middle of each line. Our solar system, at the top, shows how close many of these large extrasolar planets are to their stars. (Adapted from G. Marcy and R. P. Butler)

planet. The Doppler shift changes cyclically, and the length of time of one cycle is the period of the planet's orbit.

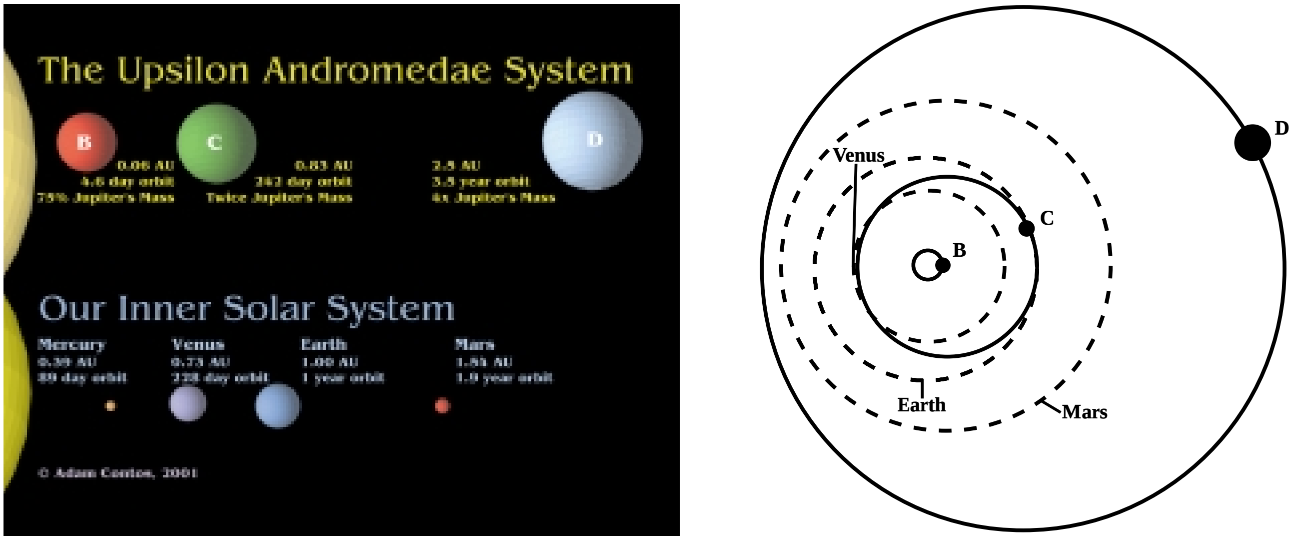
Other planets are discovered from variations in a star's proper motion, or motion among the background stars (see Chapter 4). A planet's attraction causes its star to deviate from motion in a straight line. This *astrometric* method of discovery looks for just such a wobble.

Finally, planets are located by changes in the brightness of their stars. As a planet passes between us and its star, it partially eclipses the star. Using this method in 2001, astronomers were able to study the atmosphere of a planet. As a gas giant passed in front of the star HD 209458, sodium in the planet's atmosphere absorbed certain wavelengths of starlight. This absorption was observed using the *Hubble Space Telescope*.

The astrometric method also tells us the mass of a planet. The two lowest-mass planets known with confidence have 3 or 4 times the mass of the Earth, and one may have been observed with a mass only slightly greater than that of our Moon. The vast majority, however, range between a half and a few times the mass of Jupiter, and many orbit surprisingly close to their stars (Figure II-14). From our model of how our solar system formed, these planets should have formed much farther from their stars than they are at present. Nevertheless, the solar system is one of several star systems that do not have Jupiter-sized planets located within an AU of their star.

In 1999, astronomers began discovering star systems with more than one planet. This is done by observing some stars wobbling in ways too complicated to be caused by a single planet. In a multiple planet system, each planet contributes a tug to the star. By combining the effects of two or more planets, the observed pattern of the star's motion (Doppler or astrometric) can be recovered. The first star discovered with multiple planets was Upsilon Andromedae (Figure II-15).

A dramatic consequence of the inward spiraling of planets was discovered in 2001, when the remnants of at least one planet were discovered in the atmosphere of a star that contains at least two other planets. The star's atmosphere



a b

FIGURE II-15 A Star with Three Planets (a) The star Upsilon Andromedae is believed to have at least three planets, discovered by measuring the complex Doppler shift of the star. This star system is located 44 ly from Earth and the planets all have masses similar to that of Jupiter. (b) The orbital paths of the planets, labeled B, C, and D, along with the orbits of Venus, Earth, and Mars, drawn in for comparison. (Adam Contos, Harvard-Smithsonian Center for Astrophysics)

contained a rare form of lithium that is found in planets, but which is destroyed in stars within 30 million years after they form. The presence of this isotope, ^{6}Li, means that at least one planet spiraled so close to the star that it was vaporized.

Extrasolar planets orbit a breathtaking variety of stars, including Earth-sized, burned-out hulks of stars much more massive than the Sun. Some known planets, however, do orbit stars much like our own. The vast majority of extrasolar planets have highly elliptical orbits, with eccentricities up to at least to $e = 0.71$ (see Section 2-3). Star systems with massive planets on highly eccentric orbits are unlikely to have life-sustaining earthlike planets. This is because the changing gravitational force from the massive planet is likely to prevent smaller planets from staying in stable orbits.

All the *known* extrasolar planets probably do not support life as we know it. In the first place, like our giant planets, most of them lack solid surfaces and they are composed primarily of hydrogen and helium. The terrestrial-type planets among them are orbiting only tiny stellar remnants. These stars exploded long ago with such titanic force that any life on their planets would have been annihilated. Furthermore, most extrasolar planets are so close to their stars as to be too hot for organic compounds to remain stable. Life outside the solar system may yet exist. We just have to find the right planets.

We are most likely to discover extraterrestrial life on extrasolar planets similar to Earth orbiting at about 1 AU from stars similar to the Sun. This is because stars supporting life have to last long enough for life to evolve and the planets must be at distances at which water can exist as a liquid. And the search is on, thanks to the power of adaptive optics and space telescopes. Planets are brighter at infrared wavelengths, compared to their stars, than they are at visible wavelengths. Will an infrared telescope therefore point us to the first traces of distant life?

II-7 Frontiers yet to be discovered

Despite their relative closeness to us, there are still countless objects to be discovered and studied in the solar system. The most poorly understood bodies are the Kuiper belt objects. But, as we will see in the coming chapters, virtually every other object in the solar system has secrets to be uncovered. Our understanding of the formation of the solar system also has the potential of being greatly advanced by further study of proplyds and planets orbiting other stars.

We begin a detailed exploration of the solar system by examining the two bodies we know best—the Earth and its Moon. By understanding them, we will be better able to make some sense of the remarkably alien neighboring worlds we encounter thereafter.

WHAT DID YOU THINK?

1 *How many stars are there in the solar system?* The solar system has only one star, the Sun.

2 *Was the solar system created as a direct result of the formation of the universe?* No. All matter and energy were created by the Big Bang. However, much of the material that exists in our solar system was processed inside stars that evolved before the solar system existed. The solar system formed billions of years after the Big Bang occurred.

3 *How long has the Earth existed?* The Earth formed along with the rest of the solar system 4.6 billion years ago.

4 *Is Pluto always the farthest planet from the Sun?* No. From 1979 to 1999, Neptune was the farthest planet from the Sun. This was because Pluto's orbit is highly eccentric, bringing that planet inside Neptune's orbit for about 20 years once every 250 years.

5 *What typical shape(s) do moons have?* While some moons are spherical, most look roughly like potatoes.

KEY WORDS

accretion, 119
albedo, 124
asteroid, 124
asteroid belt, 124
average density, 122
comet, 124
crater, 120
meteoroid, 124
planetesimal, 119
protoplanet, 119
protoplanetary disks (proplyds), 119
protosun, 117
solar nebula, 116
solar system, 116
terrestrial planet, 124

KEY IDEAS

• Hydrogen, helium, and traces of lithium, the three lightest elements, were formed shortly after the creation of the universe. The heavier elements were produced much later by stars and cast into space when the stars died. By mass, 98% of the matter in the universe is hydrogen and helium.

• The solar system formed 4.6 billion years ago from a swirling, disk-shaped cloud of gas, ice, and dust called the solar nebula.

• The four inner planets formed through the accretion of dust particles into planetesimals and then into larger protoplanets. The four large outer planets probably formed through the runaway accretion of gas onto rocky protoplanetary cores.

• The Sun formed at the center of the solar nebula. After about 100 million years, the temperature at the protosun's center was high enough to ignite thermonuclear reactions. For 800 million years after the Sun formed, impacts of asteroidlike objects on the young planets dominated the history of the solar system.

• The four inner planets of the solar system share many characteristics and are distinctly different from the four giant outer planets and from Pluto.

• The four inner, terrestrial planets are relatively small, have high average densities, and are composed primarily of rock and metal.

• Jupiter and Saturn have large diameters and low densities and are composed primarily of hydrogen and helium. Uranus and Neptune have large quantities of water as well as much hydrogen and helium. Pluto, the smallest of the nine planets, is of intermediate density owing to its rock-ice composition.

• Asteroids are rocky and metallic debris in the solar system larger than about a kilometer in diameter. Meteoroids are smaller pieces of such debris. Comets are debris that contain both ice and rock.

• Astronomers have observed disks of gas and dust orbiting young stars.

• At least 80 extrasolar planets have been discovered orbiting other stars.

REVIEW QUESTIONS

1 Why was Pluto recently closer to the Sun than Neptune?

2 Why do astronomers believe that the solar nebula was rotating?

INTERACTIVE EXERCISE II.1

3 To test your understanding of the formation of the solar system do Interactive Exercise II-1 on the CD-ROM or Web site. Explain what is happening in each figure. You can print out your results, if required.

4 Describe three methods that exist for discovering extrasolar planets.

ADVANCED QUESTIONS

5 What two properties of a planet must be known in order for its average density to be determined? How are these properties determined?

6 How can Neptune have more mass than Uranus but a smaller diameter? *Hint:* See Table II-2.

WHAT IF ...

7 The Earth had formed around one of the first-generation stars created in the universe? What chemical elements would the Earth then be composed of? Could we humans exist on that version of Earth? Why or why not?

8 The Earth had a highly elliptical orbit, like Pluto? What would be different about the Earth and life on it?

9 The accretion process of planet formation was still going on? How would life in general on Earth be different and how might we be different?

10 The solar system passed through a cloud of gas and dust that was beginning to collapse to form a new star and planet system? What might happen to the Earth and how would the passage affect the appearance of the sky?

WEB/CD-ROM QUESTIONS

11 Search the Web for information about recent observations of protoplanetary disks. What insights about the formation of the solar system have astronomers gained from these observations? Explain the evidence astronomers have, from these observations, that planets are forming in these disks.

12 In 2000, extrasolar planets with masses comparable to that of Saturn were first detected around the stars HD 16141 (also called 79 Ceti) and HD 46375. Search the Web for information about these planets. How do their masses compare to previously discovered extrasolar planets? Do these planets move around their stars in the same kind of orbit as Saturn follows around the Sun? If not, explain the differences.

13 Search the Web for information about the planet orbiting the star HD 209458. This planet has been detected using two methods. What are they? What have astronomers learned about this planet?

ANIMATION II.2

14 **Determining Terrestrial Planet Orbital Periods.** Access the animation “Planetary Orbits” in Essentials II of the *Discovering the Universe* Web site or CD-ROM. Focus on the motions of the inner planets during the last half of the animation. Using the stop and start buttons, determine how many days it takes Mars, Venus, and Mercury to orbit the Sun once if it takes Earth approximately 365 days.

OBSERVING PROJECTS

15 Planetarium software can help you get an overview of our solar system. We will learn more about it in the next chapters. For now, however, open your *Starry Night Backyard™* program and put it into Atlas mode (*Go/Atlas*). Turn on the planets (Sky: Planets/Sun). Describe and comment on the brightnesses of the various planets relative to the stars. Now turn on daylight (Sky: Daylight) and by changing the time determine which, if any, planets are visible in the night sky this month where you live.

16 There are many young stars still embedded in the clouds of gas and dust from which they formed. In the winter evening sky in the northern hemisphere, for example, is the famous Orion Nebula (Figure II-2). In the summer night sky in the northern hemisphere, the Lagoon, Omega, and Trifid nebulae can be observed. Examine some of these nebulae with a telescope. Describe their appearances. Try to determine which stars in your field of view are actually associated with the nebulosity. You can use the *Starry Night Backyard™* program to help you find these nebulae. Also, the table below gives their coordinates (right ascension and declination; see Section 1-2).

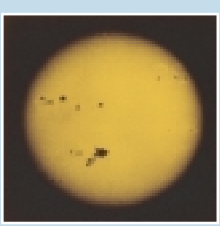
Nebula	**Right ascension**	**Declination**
Lagoon	$18^h\ 03.8^m$	–24° 23′
Omega	18 20.8	–16 11
Trifid	18 02.3	–23 02
Orion	5 35.4	–5 27

17 Use the *Starry Night Backyard™* program to observe magnified images of at least four of the planets. First go into Atlas mode (*Go/Atlas*) and then put up the planet list (Sky/Planet List). In the Planet palette, double click on the name of the planet you wish to view. When it appears, right click on it and press *magnify*. Describe the planet's appearance. From what you observe, state whether you are looking at the planet's surface or a cloud cover and justify your assertion.

An Astronomer's Almanac

Movable Type in Use

1610-1613
Galileo Galilei observes phases of Venus and major moons of Jupiter—Io, Europa, Ganymede, and Callisto—and uses observations of sunspots to demonstrate the Sun's rotation.



1655-1656
Jupiter's Great Red Spot discovered by Giovanni Cassini. Christiaan Huygens identifies Saturn's rings as rings, and discovers its moon, Titan.

1671
Giovanni Cassini calculates first relatively accurate estimate of distance between Earth and Sun.

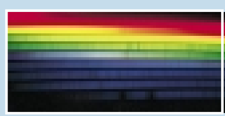
1705-1757
Edmund Halley makes first prediction of the period of a comet's orbit, calculating that the comet we now call Halley's would return in 1758. Comet's return towards inner solar system first observed by Johann Palitzsch.

American Revolution

1781-1784
William Herschel first to observe Uranus and to detect clouds around Mars.

1801
Giuseppi Piazzi discovers the asteroid Ceres.

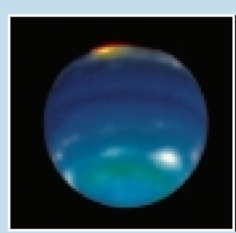
1814
Joseph von Fraunhofer studies the Sun's spectrum and catalogs 500 spectral lines.



1821
Alexis Bouvard detects irregularities in Uranus's orbit.

Telegraph in Use

1843-1849
Sunspot cycle discovered. Neptune's presence predicted independently by John Adams and Urbain Leverrier. Neptune discovered by Johann Galle; Triton discovered by William Lassell. Edouard Roche shows that Saturn's rings did not form from a preexisting moon.



1856-1859
James Clerk Maxwell proves that Saturn's rings are not solid. Richard Carrington discovers solar flares.

1861-1866
Gustav Kirchhoff uses spectral analysis to determine the chemical composition of the Sun's atmosphere. Richard Carrington discovers the Sun's differential rotation. Giovanni Schiaparelli detects meteor showers caused by Earth passing through comet debris.

Telephone

1877
Phobos and Deimos discovered by Asaph Hall. Giovanni Schiaparelli observes "*canali*" (Italian for "channels") on Mars.

1906
First Trojan asteroid, Achilles, discovered by Max Wolf. Limb darkening explained by Karl Schwarzschild.

The Solar System

1908
George Hale shows sunspots to be magnetic phenomena.

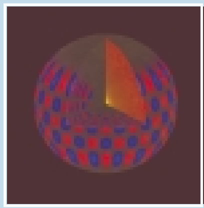
1923
Arthur Eddington calculates that an equilibrium between gravity and radiation maintains the Sun at its size.

1930
Clyde Tombaugh discovers Pluto.

1938
Fusion shown to be source of Sun's energy.

1950-1959
Oort Comet cloud proposed by Jan Oort. Kuiper belt of comet bodies proposed by Gerard Kuiper. Solar wind discovered by Eugene Parker. Soviet *Luna* missions: *Luna 1*, first lunar flyby; *Luna 2*, first lunar impact; *Luna 3* flyby, first photo of lunar far side.

1960-1964
Five-minute solar oscillations detected. Venus' retrograde rotation measured. Mercury's rotation rate determined by Arecibo radio observatory. U.S. missions: *Mariner 4*, first flyby of Mars; *Ranger 7*, first successful U.S. lunar impact.

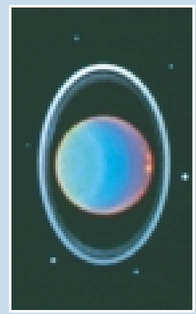


1966-1967
Soviet *Luna 13*, first soft landing on Moon; 2 successful *Lunas, 16* and *17*, (robot and rover) followed. U.S. *Suryeyor 1*, first of 4 successful soft landings on the Moon. U.S. *Lunar Orbiter 1*, first of 4 successful orbiters. Soviet *Venera 4* makes first landing on Venus.

1969-1972
U.S. *Apollo* mission: *Apollo 11*, first humans to land on the Moon; *Apollo 12, 14, 15, 16,* and *17* landings all successful; failed *Apollo 13* grows legendary.

1970-1976
First landers on Mars: Soviet *Mars 2* and *3* spacecraft. U.S. *Mariner 10*, first spacecraft to visit Mercury. First U.S. landings on Mars by *Viking 1* and *2* spacecraft.

1977-1978
James Elliot discovers rings of Uranus. James Christy discovers Pluto's moon, Charon.



1979-1989
Voyager I and *II* spacecraft visit outer planets, discovering Jupiter's and Neptune's rings, among other things.

1990-1998
Magellan spacecraft completes full radar map of Venus. *Clementine* orbiter discovers evidence of water on Moon. *Galileo* spacecraft visits Jupiter system. Mars lander sends rover *Sojourner* to study Martian surface. Lunar orbiter, *Prospector*, confirms water ice reservoir of some 3 billion tons at the Moon's poles.

2001
Near shoemaker spacecraft lands on asteroid Eros.

in Use

Cold War

Communications Satellites in Use

Berlin Wall Falls