Chapter 15

The Solar System

Earth is a planet that is just right for living things — and among them are people who have long wondered if other planets have life. Mars and Europa (a moon of Jupiter) are good candidates for having extraterrestrial life, but are only just candidates. Space probes have explored only a tiny fraction of the surfaces of Mars and Venus looking for signs of life, and the small amount of evidence collected gives no definite answers. If you were asked to describe a creature that could live on each of the planets (or moons) in the solar system, what characteristics would it have? What would it eat? How would it move? A creature on Venus might have to live at a surface temperature of 500°C. Neptune's environment is frozen; what type of creature could live there? In this chapter, you will learn about the vast, unexplored territories that are the planets and moons of the solar system.

Key Questions

1. *What is the solar system and how does it stay together?*
2. *How do the other planets in the solar system compare with Earth? Could they support life?*
2. *What else is there in the solar system besides the sun and planets?*

Footnote: On August 24, 2006, the International Astronomical Union (IAU) passed a new definition of a planet. The new definition excludes Pluto as a planet. According to the new definition, Pluto is classified as a "dwarf planet."

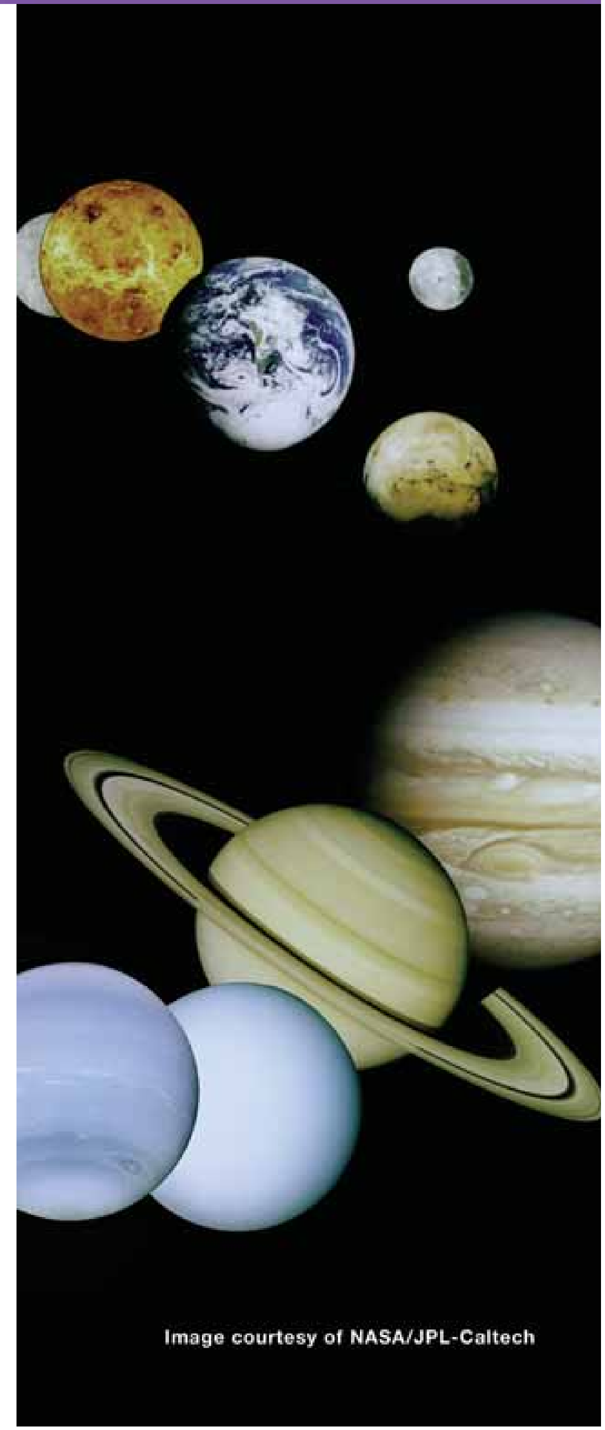


Image courtesy of NASA/JPL-Caltech

15.1 The Solar System

Ancient observers noticed that five bright objects seemed to wander among the stars at night. They called these objects *planets*, from the Greek word meaning "wandering star," and named them Mercury, Venus, Mars, Jupiter, and Saturn. In A.D. 140, the Greek astronomer Ptolemy "explained" that planets and the moon orbited Earth. For the next 1,400 years, people believed those ideas, until science proved Ptolemy wrong.

How the solar system was discovered

Planets shine by reflecting sunlight

Today we know that **planets** are not stars. Stars give off their own light. We see the planets *because they reflect light from the sun*. For example, Venus appears as a crescent like the moon, becoming dark at times. This is because Venus does not give off its own light. When Earth is on the same side of the sun as Venus, we see Venus's shadowed side (Figure 15.1 top). The phases of Venus were discovered by Galileo in the 1600s and were part of the evidence that eventually overturned Ptolemy's model of the solar system.

Changing ideas about the solar system

Almost 100 years before Galileo, Polish astronomer Nicolaus Copernicus had proposed that the planets orbited the sun, but few believed him. Then came Galileo, using a telescope he built himself to make two discoveries that strongly supported Copernicus's ideas. First, he argued that the phases of Venus could not be explained if Earth were at the center of the planets (Figure 15.1). Second, he saw that there were four moons orbiting Jupiter. This showed that not everything in the sky revolved around Earth.

Discovery of the outer planets

The distant planets Uranus and Neptune are far from the sun and don't reflect much light back to Earth. These planets were not discovered until telescopes became large enough to see very faint objects. The dwarf planet Pluto is so far away that even today we have only a blurry image of it. Astronomers believe that many objects like Pluto may orbit the sun beyond Neptune's orbit in the *Kuiper Belt*. These objects reflect so little sunlight that the two largest (Pluto-sized) ones have only just recently been discovered.

VOCABULARY

planet - a massive object orbiting a star, like the Sun. A true planet has cleared the neighborhood around its orbit and has enough mass so that its gravity forms it into a spherical shape.

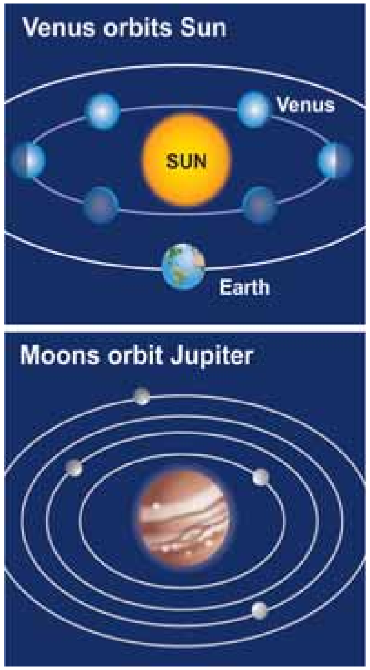


Figure 15.1: *Two of Galileo's discoveries that helped prove that Earth and the other planets orbit the sun. The top diagram shows how the phases of Venus are due to its orbit around the sun. The bottom diagram depicts moons orbiting Jupiter. This observation proved that not all objects revolve around Earth.*

Organization of the solar system

The sun, planets, and other objects

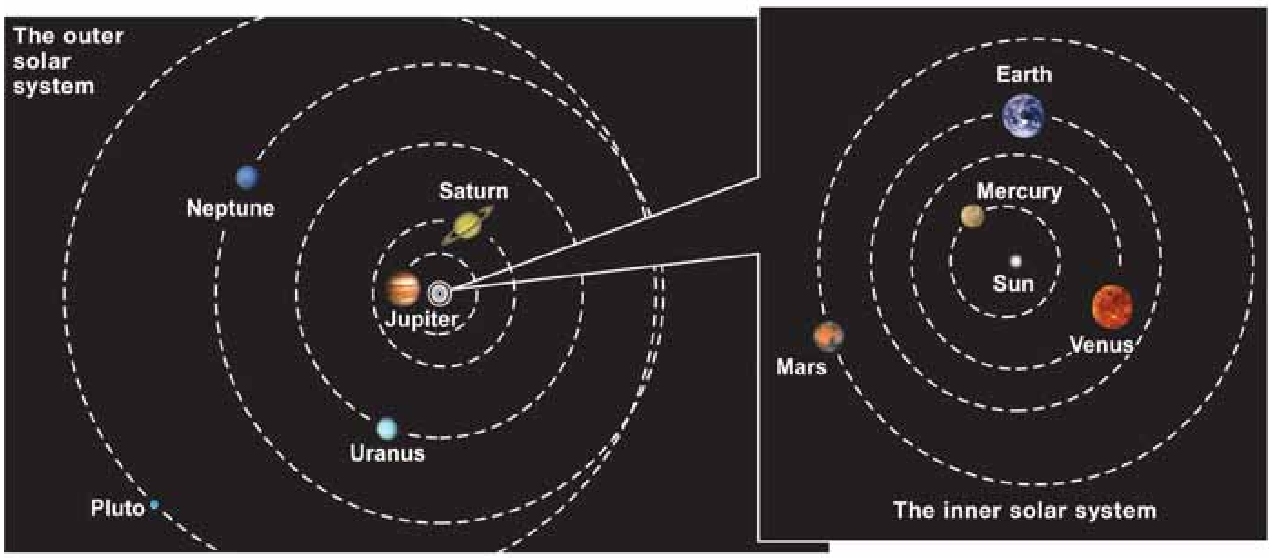
Today, we define the **solar system** as the sun and all objects that are gravitationally bound to the sun. The gravitational force of the sun keeps the solar system together just as gravity keeps the moon in orbit around Earth.

The solar system includes eight major planets and their moons (also called **planetary satellites**), and a large number of smaller objects (dwarf planets, asteroids, comets, and meteors).

VOCABULARY

solar system - the sun, planets, and their moons, and other objects that are gravitationally bound to the sun.

planetary satellite - small body of matter that orbits a planet.



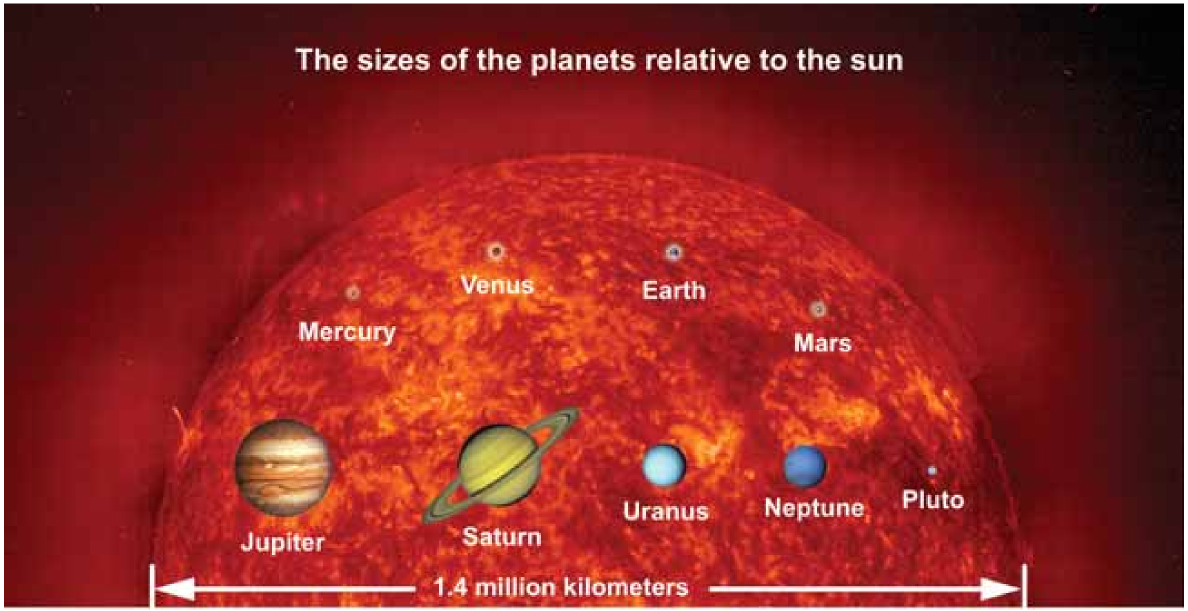
Inner and outer planets

The solar system is roughly divided into the inner planets (Mercury, Venus, Earth, Mars) and the outer planets (Jupiter, Saturn, Uranus, Neptune) The dwarf planet Pluto is the oldest known member of a smaller group of frozen worlds orbiting beyond Neptune. The diagram above shows the orbits of the planets to scale (the planets, however, are really MUCH smaller than shown). Notice that Neptune is farther from the sun than Pluto over part of its orbit.

The orbits of the planets are not true circles, but *ellipses*. While the actual paths are close to circles, the sun is not at the center, but is off to one side. For example, Mercury's orbit is shifted 21 percent to one side of the Sun.

Comparing size and distance in the solar system

Relative sizes The sun is by far the largest object in the solar system. The next largest objects are the planets Jupiter, Saturn, Uranus, and Neptune. As you can see from the scale diagram below, the planets Mercury, Venus, Earth, Mars, and the dwarf planet Pluto appear as small dots compared with the size of the sun.



Distance Astronomers often use the distance of Earth from the sun as a measurement of distance in the solar system. One **astronomical unit** (AU) is equal to 150 million kilometers, or the distance from Earth to the sun. Mercury is 58 million kilometers from the sun. To convert this distance to astronomical units, divide it by 150 million kilometers (or 58 by 150). Mercury is 0.39 AU from the sun. Figure 15.3 lists the planets and the distance of each of them from the sun in astronomical units.

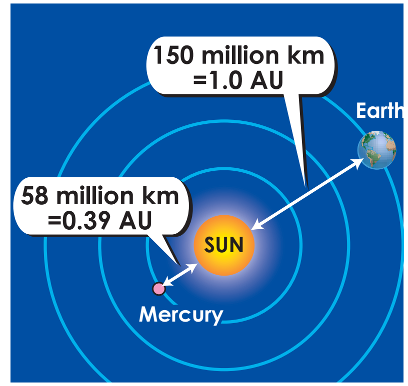


Figure 15.2: *One astronomical unit (AU) is equal to 150 million kilometers. If Earth is 1.0 AU from the sun, then Mercury, with a distance of 58 million kilometers, is 0.39 AU from the sun.*

Planet	Average distance from the sun (AU)
Mercury	0.39
Venus	0.72
Earth	1.0
Mars	1.5
Jupiter	5.2
Saturn	9.5
Uranus	19.2
Neptune	30.0
Pluto (dwarf)	39.4

Figure 15.3: *Distances of the planets from the sun in astronomical units (AU).*

Gravitational force

All objects attract The force of gravity that you are most familiar with is the one between you and Earth. We call this force your *weight*. But gravitational force is also acting between the sun, Earth, and the planets. *All objects* that have mass attract each other through gravitational forces. For example, a gravitational force exists between you and this book, but you cannot feel it because both masses are small (Figure 15.4). You don't notice the attractive force between ordinary objects because gravity is a relatively weak force.

Gravitational force is relatively weak It takes an extra-large mass to create gravitational forces that are strong enough to feel. You notice the gravity between you and Earth because Earth's mass is huge. We usually only notice gravitational forces when one of the objects has the mass of a star or planet.

Gravitational force and mass **Newton's law of universal gravitation** explains how the strength of the force depends on the mass of the objects and the distance between them. The force is *directly proportional* to each object's mass. This means the force goes up by the same factor as the mass. Doubling the mass of either of the objects doubles the force. Doubling both masses quadruples the force.

Gravitational force and distance The distance between objects also affects gravitational force. The closer objects are to each other, the stronger the force between them. The farther apart, the weaker the force. The decrease in gravitational force is proportional to the inverse square of the distance from the center of one object to the center of the other. Doubling the distance divides the force by four (2^2). If you are twice as far from an object, you feel one-fourth the gravitational force.

Gravity on Earth and the moon The strength of gravity on the surface of Earth is 9.8 N/kg. Earth and a one-kilogram object attract each other with 9.8 newtons of force. In comparison, the strength of gravity on the moon is only 1.6 N/kg. Your weight on the moon would be one-sixth what it is now. The moon's mass is much less than Earth's, so it creates less gravitational force.

VOCABULARY

Newton's law of universal gravitation - the force of gravity between objects depends on their masses and the distance between them.

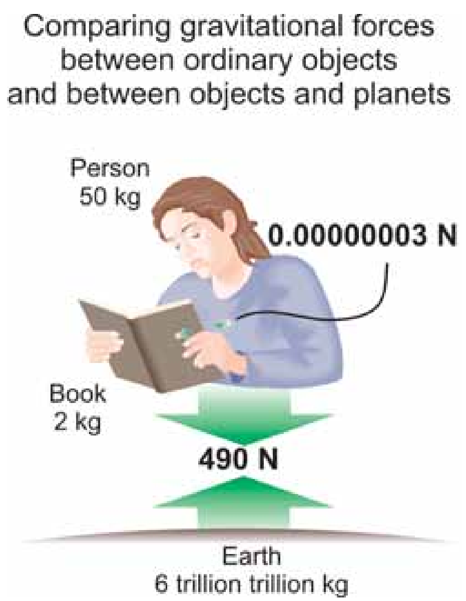


Figure 15.4: *The gravitational force between you and Earth is stronger than the force between you and your book because of Earth's large mass.*

Orbital motion

Why the moon does not fall to Earth

Earth and the other planets orbit the sun. Why doesn't the force of gravity pull the Earth into the sun (or the moon into Earth)? To answer the question, imagine kicking a ball off the ground at an angle (Figure 15.5). If you kick it at a slow speed, it curves and falls back to the ground. The faster you kick the ball, the farther it goes before hitting the ground. If you kick it fast enough, the curve of the ball's path matches the curvature of Earth. The ball goes into orbit instead of falling back to Earth.

Inertia and gravitational force

Orbital motion is caused by the interaction between inertia and gravitational force. According to Newton's first law, inertia causes objects to tend to keep moving in a straight line. Force is needed to change an object's speed or direction. Earth has a tendency to move in a straight line, but the gravitational force from the sun causes its direction of motion to curve toward the sun, into an orbit.

The size of an orbit depends on speed and mass

The radius of an orbit is a balance between gravity and inertia. Gravity gets stronger as a planet's orbit gets closer to the sun, forcing a tighter curve into the planet's motion. Increasing a planet's speed or mass has the opposite effect. Higher speed or mass increase the tendency of a planet to move in a straight line, resulting in larger, less curved orbits. Each planet orbits at the precise radius where its mass and speed are in balance with the gravity of the sun.

The shape of an orbit

The sun's gravity always pulls the planets toward it. This force would create a perfectly circular orbit IF a planet's velocity vector were *exactly* at right angles to its radius from the sun. As the solar system formed from swirling gases, interactions between planets caused slight variations in velocity vectors. As a result, the orbits of the planets are ellipses instead of perfect circles. Dwarf planet Pluto has the most elliptical orbit. However, the deviation from circular is quite small. Even Pluto's orbit is "squashed" only about 4 percent out of round. Much more significant, the sun is at a point called the *focus* that is offset from the center. This causes the distance from the sun to change as a planet orbits.

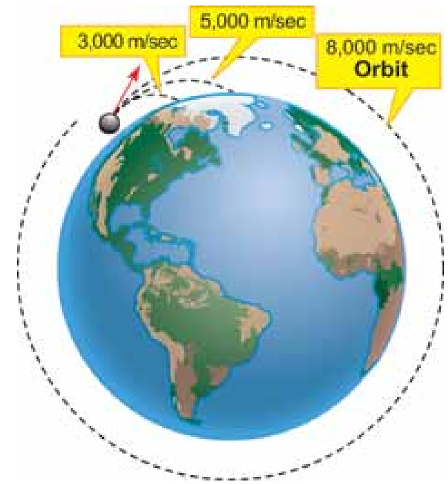


Figure 15.5: *An object launched at 8,000 meters per second will orbit Earth.*

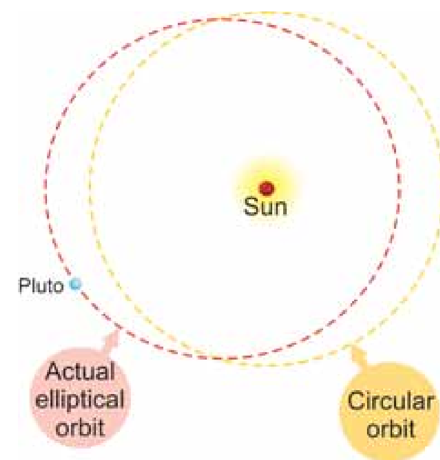


Figure 15.6: *Orbits are mathematically ellipses but are close to (shifted) circles.*

An overview of the planets

Classifying the planets

The planets are commonly classified in two groups. The **terrestrial planets** include Mercury, Venus, Earth, and Mars. The terrestrial (rocky) planets are mostly made of rock and metal. They have relatively high densities, slow rotations, solid surfaces, and few moons. The **gas planets** include Jupiter, Saturn, Uranus, and Neptune. They are made mostly of hydrogen and helium. These planets have relatively low densities, rapid rotations, thick atmospheres, and many moons. Pluto is neither terrestrial nor gas, but in a class of its own. Table 15.1 compares the planets.

VOCABULARY

terrestrial planets - Mercury, Venus, Earth, and Mars.

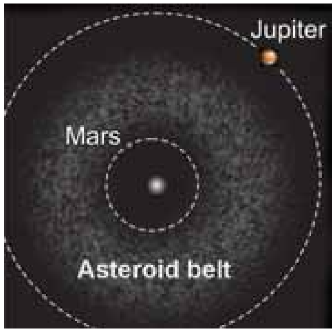
gas planets - Jupiter, Saturn, Uranus, and Neptune.

Table 15.1: Comparing properties of the planets

Property	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto (dwarf)
Diameter *(km)*	4,878	12,102	12,756	6,794	142,796	120,660	51,200	49,500	2,200
Mass *(kg)*	3.3×10^{23}	4.9×10^{24}	6.0×10^{24}	6.4×10^{23}	1.9×10^{27}	5.7×10^{26}	8.7×10^{25}	1.0×10^{26}	1.3×10^{22}
Density *(g/cm^3)*	5.44	5.25	5.52	3.91	1.31	0.69	1.21	1.67	1.75
Average distance from sun *(million km)*	58	108	150	228	778	1430	2870	4500	5910
Major moons *(#)*	0	0	1	2	39	30	21	8	1
Strength of gravity *(N/kg)*	3.7	8.9	9.8	3.7	23.1	9.0	8.7	11.0	0.6
Surface temperature *(°C)*	-170 to +400	+450 to +480	-88 to +48	-89 to -31	-108	-139	-197	-201	-223
Rotation period *(Earth days)*	59	243	1	1.03	0.41	0.43	0.72	0.67	6.4
Revolution period *(Earth years)*	0.24	0.62	1	1.9	12	29	84	165	249
Orbital speed *(km/sec)*	47.89	35.04	29.80	24.14	13.06	9.64	6.80	5.43	4.74

Asteroids and comets

Asteroids



Between Mars and Jupiter, at a distance of 320 million to 495 million kilometers, there is a huge gap that cuts the solar system in two. This gap is called the *asteroid belt* because it is filled with thousands of small, rocky bodies called *asteroids*. An **asteroid** is an object that orbits the sun but is too small to be considered a planet. So far, more than 10,000 asteroids have been discovered and more are found each year.

The size of asteroids

Most asteroids are small — less than a kilometer in diameter — but many have been found that are over 250 kilometers in diameter. The largest asteroid, named Ceres, is 933 kilometers (580 miles) across. While the majority of asteroids are found in the asteroid belt, many have highly elliptical orbits that allow them to come close to Mercury, Venus, and even Earth. About 65 million years ago, a large asteroid hit Earth near Mexico, leaving a huge crater. Some scientists believe this event led to the extinction of the dinosaurs.

Comets

We believe **comets** are made mostly of ice and dust. The ones we can detect are about the size of an Earth mountain. Comets revolve around the sun in highly elliptical orbits. In 1997, the comet Hale-Bopp could be clearly seen in the night sky without a telescope. However, we still know little about the composition and structure of comets. Several recent spacecraft have made close approaches and each new piece of evidence they gather has lead to new insights about what comets are made of and how they formed.

Evolution of a comet

As a comet approaches the sun, some of its ice turns into gas and dust and forms an outer layer called a *coma*. The inner core of the comet is the *nucleus*. As a comet gets closer to the sun, it forms a *tail*. A comet's tail can stretch for millions of kilometers into space and faces away from the sun as the comet continues its orbit (Figure 15.7). Each time a comet passes the sun, it loses some mass.

VOCABULARY

asteroid - an object that orbits the Sun but is too small to be considered a planet.

comet - an object in space made mostly of ice and dust.

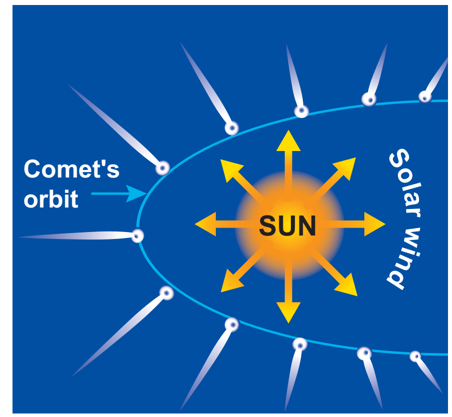


Figure 15.7: *A comet's tail faces away from the sun and can stretch for millions of kilometers in space.*

Meteors and meteorites

Meteors Occasionally, chunks of rock or dust break off from a comet or asteroid and form a **meteor**. Imagine a tennis ball traveling at about 30,000 miles per hour. That's about the size and speed of most meteors. These chunks of dust or rock travel through space and some of them end up hitting Earth's atmosphere. When this happens, meteors rub against air particles and create friction, heating them to more than 2,000°C. The intense heat vaporizes most meteors, creating a streak of light known as a "shooting star." Occasionally, larger meteors cause a brighter flash called a *fireball*. These sometimes cause an explosion that can be heard up to 30 miles away. If you live or find yourself away from any city lights, look at the sky on a clear night and chances are that, if you look long enough, you will see a meteor. On average, a meteor can be seen in the night sky about every 10 minutes.

Meteor showers When a comet nears the sun, a trail of dust and other debris burns off and remains in orbit around the sun. As Earth orbits the sun, it passes through this debris, creating a *meteor shower* as the small bits of dust burn up in the atmosphere. During a meteor shower, you can see tens and even hundreds of meteors per hour. Because Earth passes the same dust clouds from comets each year, meteor showers can be predicted with accuracy.

Meteorites

If a meteor is large enough to survive the passage through Earth's atmosphere and strike the ground, it becomes a **meteorite**. Meteorites are thought to be fragments from collisions involving asteroids. Most meteorites weigh only a few pounds or less and cause little damage when they hit. Most fall into the oceans that cover almost three-quarters of our planet's surface. Meteor Crater in Winslow, Ariz., is believed to have been caused by a giant, 50-meter diameter meteorite about 50,000 years ago. The Holsinger meteorite (Figure 15.8) is the largest known piece of this 300,000-ton meteorite, most of which vaporized on impact.

VOCABULARY

meteor - a chunk of burning rock traveling through Earth's atmosphere.

meteorite - a meteor that passes through Earth's atmosphere and strikes the ground.

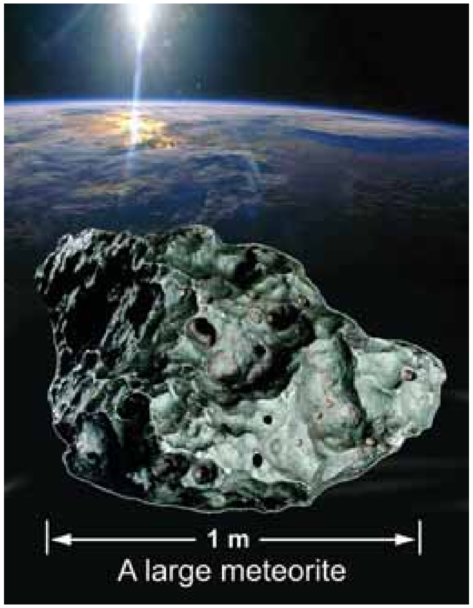


Figure 15.8: *The Holsinger meteorite is a large piece of a much larger meteorite that blasted out Meteor Crater in Arizona about 50,000 years ago. This meteorite, while no taller than your thigh, weighs 1,400 lbs.*