Chapter 26

Earth and Its Moon

THE RACE FOR THE MOON

Ever since Galileo made his first telescopic observations of the moon's surface in 1609, humans have dreamed of visiting Earth's closest neighbor. A series of events in the mid-twentieth century changed that dream into reality. During the Second World War, the German military developed rockets that were capable of long-range guided flight.

Based on this technology, the Russians launched the first artificial satellite into orbit around Earth in 1957. This began the "space race" between the Soviet Union and the United States. In addition to the first artificial satellite, the achievements of the Soviet Union included the first human to travel outside Earth's atmosphere, the first unmanned crash landing on the moon, and the first photographs of the far side of the moon.

Apollo Program

American politicians and scientists were embarrassed by the early triumphs of their rival. Thus began the American program to explore space, which led to the Apollo program of

Figure 26-1 The last Apollo mission in 1972 carried geologist Harrison Schmitt to the surface of the moon. The six manned moon landings greatly expanded scientists' understanding of Earth's nearest neighbor in space.

lunar exploration. In July of 1969, American astronaut Neil Armstrong became the first human to set foot on the surface of the moon. That mission also returned the first samples of moon rock to Earth. In the next six Apollo missions, a total of 382 kg (842 pounds) of moon rocks were brought back to Earth for scientific study. Figure 26-1 is a photograph of geologist and Apollo 17 crew member Harrison Schmitt investigating the lunar surface. Since that last Apollo mission in 1972, no other humans have visited the moon.

Among the many discoveries of the Apollo program, scientists learned that the mineral composition of the surface of moon is very similar to the composition of Earth's mantle. Plagioclase feldspar, pyroxene, and olivine are the most common minerals in the lunar samples.

Lunar Surface

The surface of the moon has two landscape types, the lunar highlands and the maria (from the Latin word for "seas"). The rocks of the lunar highlands are mostly anorthosite, a rock type widespread in New York's Adirondack Mountains, but not common in most places on Earth. The lunar maria are relatively flat and darker in color than the highlands. They are composed of basalt, a relatively common dark-colored, fine-grained, igneous rock on Earth.

The moon has none of Earth's most common sedimentary rocks because it has no atmosphere or surface water. Chemical weathering does not occur on the moon, although the surface is covered by material from meteorites and moon rocks broken by meteorite impacts. However, breccia, a rock formed from the breakage and welding of rock fragments, is found in the lunar highlands. Radiometric dating has shown the oldest moon rocks are about the same age as Earth, 4.6 billion years.

ACTIVITY 26-1 LUNAR SURVIVAL KIT

Imagine that you are part of a team chosen to explore the moon. You were scheduled to land near the mother ship, which will take you back to Earth. Unfortunately, you were forced to land 100 km from the rendezvous point on the lighted side of the moon. None of your crew is injured, but you need to select the most important items for your survival. Arrange the 15 items below from the most important item (#1) to the least useful (#15). Then, for each item, briefly explain why you gave it that priority.

List of items:
box of matches, dry food concentrate, 15-m nylon rope, parachute silk 6 m by 6 m, portable heater, two .45 caliber pistols, 4 liters of dehydrated milk, three 50-kg tanks of oxygen, chart of the constellations, first aid kit, solar powered receiver–transmitter, 20 liters of water, ocean life raft, five signal flares, flat metal mirror 10 cm by 10 cm

WHAT IS THE HISTORY OF EARTH'S MOON?

A moon is a natural satellite of a planet. A **satellite** is an object in space that revolves around another object under the influence of gravity. The moon is Earth's only natural satellite. (Earth, like the other planets, is a satellite of the sun.) Although Mercury and Venus have no moons, all the other planets do have natural satellites. Earth is the only planet in our solar system with a single moon.

Our moon is the largest compared with the planet it orbits. The moon's diameter is a little more than a quarter of Earth's diameter. In fact, our moon is larger than the dwarf planet, Pluto.

Another curious feature of our moon is the fact that its period of rotation and revolution are the same, about $27\frac{1}{3}$ days. Consequently, the same side of the moon always faces Earth. This is why features of the far side of the moon were unknown until the Soviets sent a satellite around the moon to take photographs early in the "space race."

The Origin of Earth's Moon

There have been several theories about the origin of the moon. Some astronomers have suggested that the moon and Earth formed as a double planet orbiting the sun. Others have speculated that the moon was an object in space that came close enough to Earth to be captured by Earth's gravity.

Most astronomers now agree that a collision between Earth and a smaller planet probably created the moon shortly after Earth's formation. That impact destroyed the smaller planet and created a debris field in space. The debris came together under the influence of gravity, forming our moon.

Surface Features of the Moon

The cratered surface of the moon contrasts sharply with Earth's surface. Many large objects undoubtedly hit the moon and Earth. The highlands of the moon have been solid for more than 4 billion years. They are so covered with impact craters that the surface seems to be made of crater upon crater.

The moon is small enough and its gravity weak enough that the moon was unable to hold an atmosphere. Consequently, there is no shell of gases surrounding the moon and no water on the moon's surface to cause weathering, erosion, and deposition. Furthermore, unlike Earth, the surface of the moon is not composed of active tectonic plates that create and recycle surface material. Therefore, features on the moon last much longer than they do on Earth. The only active process on the moon is impact by meteoroids and other objects from space. Early in the history of the solar system, there were many more of these objects and impacts were far more common.

It is clear from the dark lava flows that became the maria that the moon once had a molten interior. Most of the moon's volcanic eruptions occurred between 3.8 and 3.1 billion years ago. The maria show less cratering than the highlands because most of the impacts that created the largest craters occurred before the surface of the maria had formed. By 3 billion years ago, the surface of the moon probably looked pretty much as it does today. Whether the moon still has molten rock in its interior is a question that scientists have not yet settled.

HOW CAN WE DESCRIBE ORBITS?

The earliest astronomers believed that the sky was a giant dome that covers Earth from horizon to horizon. The gradual realization that Earth is a sphere led to the idea that the sky is a larger sphere that surrounds Earth. The wandering motion of the planets led to the idea that planets and the moon move in orbits independent of the fixed stars. These orbits were originally thought to be circles. However, careful observations of the planets showed that their motions could be explained best if their orbits were not circles, but ellipses.

An **ellipse** is a closed curve formed around two fixed points such that the total distance between any point on the curve and the fixed points is constant. The fixed points are known as the foci of the ellipse. (The singular of foci is focus.)

If you use pins and a loop of string to draw an ellipse, the position of each pin is a **focus** of the ellipse. The string keeps the total distance to the two foci constant.

In all orbits, the object the satellite revolves around, known as the primary, is located at one focus. For example, the Earth is at one focus of the moon's orbit. The sun is also located at one focus in Earth's orbit. The other focus is a point in empty space. You should also note that Earth is not at the center of the moon's orbit and the sun is not at the center of Earth's orbit.

ACTIVITY 26-2 ORBIT OF THE MOON

Obtain the following materials: one soft board approximately 12 inches (30 cm) square (fiberboard, ceiling tile, or soft pine work well), two straight pins, adhesive tape, one piece of light string about 30–40 cm long, one sharp pencil, one clean sheet of standard size paper ($8\frac{1}{2}$ inches by 11 inches), one metric ruler.

Find the center of the sheet of paper by drawing two lines connecting opposite corners of the paper.

1. Tie the string into a loop that is 10 cm long when fully stretched (± 0.5 cm).
2. Tape the paper to the soft board.
3. Stick one pin through the center of the sheet of paper and into the soft board. Place the loop of string around it. Then stretch the loop to its greatest distance with the tip of the pencil. Keeping the loop taut and the pencil perpendicular to the paper, make a circle around the pin. Label it "circle" along its circumference.
4. Place the two pins 4.5 cm from the center of the paper along the paper's long axis. Stretch the string around both pins and then draw out the string to make an ellipse.
5. Make another ellipse by placing the two pins 1 cm apart (0.5 cm each side of the center). Draw this ellipse and label it "Orbit of the Moon."

   Is the "Orbit of the Moon" noticeably elongated?

Calculating Eccentricity

The shape of an orbit is described by its **eccentricity**, or how elongated the ellipse is. The following equation, used to calculate the eccentricity of an ellipse, is found in the *Earth Science Reference Tables*:

$$Eccentricity = \frac{distance\ between\ foci}{length\ of\ major\ axis}$$

Whenever you are asked to calculate eccentricity, either the values will be given to you or a diagram will be provided that clearly shows the ellipse and the position of the two foci. If you are given a diagram, you will need to use a centimeter scale to measure these two distances. Remember that a centimeter scale is printed on the front cover of the *Earth Science Reference Tables.* The **major axis** is the distance across the ellipse measured at its widest point. (The smaller axis, the width of the ellipse, is known as the minor axis.) These two features of an ellipse are shown in Figure 26-2.

SAMPLE PROBLEMS

Problem 1 Calculate the eccentricity of the ellipse in Figure 26-2.

Solution The distance between the foci of this ellipse is 3 cm. The distance across the ellipse (the major axis) is 4 cm. The calculation is shown below.

$$\begin{aligned} Eccentricity &= \frac{distance\ between\ foci}{length\ of\ major\ axis} \\ &= \frac{3\ \text{cm}}{4\ \text{cm}} \\ &= 0.75 \end{aligned}$$

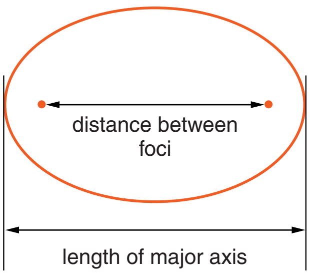

Figure 26-2 Eccentricity is calculated by dividing the distance between the foci of an ellipse by the length of the major axis. Eccentricity is a ratio without units.

Notice that there are no units of eccentricity. Eccentricity is a ratio between two measured values.

Problem 2 The greatest distance across Earth's orbit is 299,200,000 km. The distance from the sun to the location in space that is the other focus of Earth's orbit is 5,086,400 km. Calculate the eccentricity of Earth's orbit.

Solution

$$\begin{aligned} \textit{Eccentricity} &= \frac{\textit{distance between foci}}{\textit{length of major axis}} \\ &= \frac{5{,}086{,}400\text{ km}}{299{,}200{,}000\text{ km}} \\ &= 0.017 \end{aligned}$$

Notice that the result is a very small number. Earth's orbit is nearly a perfect circle. That is why the changing distance between Earth and the sun is not a significant factor in seasonal changes in temperature on Earth.

Problem 3 The greatest distance across Mars' orbit is 455,800,000 km. The eccentricity of its orbit is 0.093. What is the approximate distance between the sun and the second focus of Mars' orbit?

Solution The first step is to rearrange the formula to isolate the distance between the foci. Multiplying both sides of the equation by *length of major axis* does this.

$$\textit{Eccentricity} = \frac{\textit{distance between foci}}{\textit{length of major axis}}$$

The next step is to substitute the values and solve for the distance between the foci:

$$\begin{aligned} \textit{Length of major axis} \times \textit{Eccentricity} &= \textit{distance between foci} \\ 455{,}800{,}000\text{ km} \times 0.093 &= \textit{distance between foci} \\ 42{,}389{,}400\text{ km} &= \textit{distance between foci} \end{aligned}$$

This value is expressed to a much greater accuracy than the length of the major axis of the ellipse. So it should be rounded off to 42 million km. (Also note that the problem asked for the "approximate distance.")

☑ *Practice Problem 1*

Calculate the eccentricity of an ellipse in which the distance between the foci is 15 cm and the length of the major axis is 60 cm.

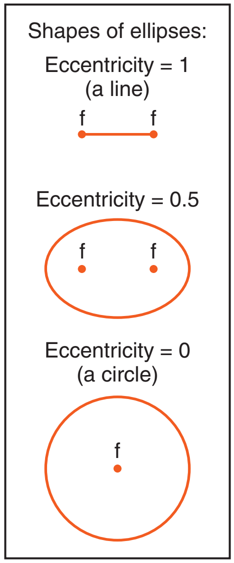

Figure 26-3 The orbits of Earth and the moon look like circles. Only by carefully measuring the length and width of the orbits, or by locating the two foci, can scientists observe that the orbits of the moon and Earth are not quite circles.

Practice Problem 2

The greatest distance across the moon's orbit is 772,000 km; the eccentricity of its orbit is 0.055. How far apart are the foci of the moon's orbit?

Figure 26-3 shows the range of shape of ellipses. If the foci are at the ends of the ellipse, the ellipse will be a line segment with an eccentricity of 1. If the two foci are located near the ends of the ellipse, the ellipse looks flattened. A circle is the special case of ellipse in which the foci are at a single point. The eccentricity of a circle is 0. When considering the eccentricity of an ellipse, it may help to remember that just as the number "1" can be written as a line, an ellipse with an eccentricity of one is a straight line. Furthermore, just as the number "0" can be written as a circle, an ellipse with an eccentricity of zero is a circle.

WHAT DETERMINES A SATELLITE'S S ORBIT?

The path that Earth takes around the sun is determined by two factors: inertia and gravity. **Inertia** is the tendency of an object at rest to remain at rest or an object in motion to move at a constant speed in a straight line unless acted on by an unbalanced force. If you roll a heavy ball across a flat, hard floor, the ball continues in a straight line until some force causes it to change its speed or its direction. That force could be friction with the floor causing the ball to slow down. It could be a force applied by an object or a wall as the ball collides with it. On the other hand, it could be someone pushing the ball to one side, causing the ball to change direction. Similarly, an object moving through space will move in a straight line unless some force causes it change its speed or its direction.

Gravity

The moon, planets, and other satellites follow curved paths. This tells you that a force must be acting on them. That force is gravity. **Gravity** is the force of attraction between all objects. If the objects are relatively small, such as your body and familiar objects around you, that force is so small you cannot feel it. Although your body's mass is small, the mass of Earth is very large. Therefore, the force of gravity is quite noticeable. **Weight** is the force of attraction between your body and Earth.

When the mass of either or both objects increases, the gravitational force between them also increases. Therefore, a person would weigh more on a more massive planet. Correspondingly, you would weigh less on Mars or the moon than you do on Earth because these smaller celestial bodies have less mass than Earth.

Gravity also depends on the distance between the centers of the two objects. People who climb to the top of high mountains experience a very small but measurable decrease in their weight. This is because they are moving away from Earth's center. In fact, the higher a person goes above Earth's surface, the less the person weighs.

The motion of Earth or any celestial object in its elliptical orbit can be thought of as a combination of two kinds of motion. The first is straight-line motion under the influence of inertia. The second is falling motion toward the primary of

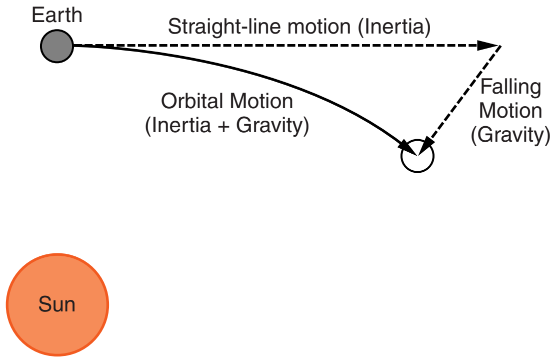

Figure 26-4 The curved motion of the moon in its orbit is the result of straight-line motion caused by inertia, and its falling path toward Earth caused by gravity.

the satellite under the influence of gravity. The result is a curved path as shown in Figure 26-4.

Orbital Energy

The orbital energy that Earth has is a combination of kinetic and potential energy. The potential energy is a result of the distance between Earth and the sun. Kinetic energy is the speed of Earth in its orbit. The combined energy remains constant unless it is reduced by friction. However, there is no friction in space. The balance between the two components of orbital energy, speed and orbital distance, does change. As a satellite moves farther from its primary, its orbital speed decreases. As it moves closer, its speed increases. Figure 26-5 is

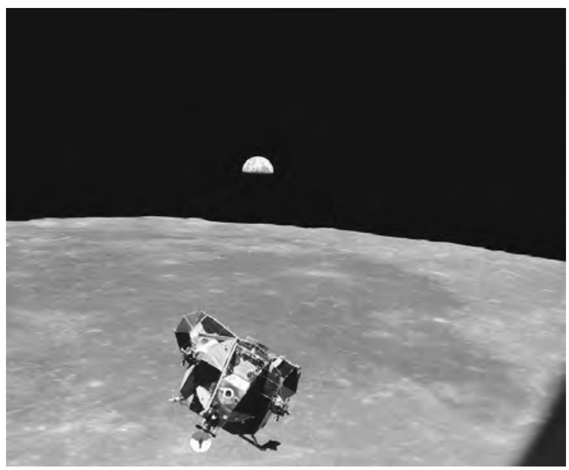

Figure 26-5 In this photograph, the lunar module craft is a satellite orbiting the moon. The moon is a satellite of Earth; Earth is a satellite of the sun.

a photograph of Earth taken from a spacecraft in orbit around the moon.

Moving in an ellipse, Earth changes its distance from the sun by a small amount. Therefore, Earth's speed in its orbit changes. In fact, for all planets orbiting the sun, orbital speed is a function of the distance between the satellite and the primary. Earth moves a little faster when it is closer to the sun and slower when it is farther from the sun. Earth is closest to the sun in early January, which is when its orbital speed is greatest (although the change is relatively small). The moon also changes speed in its orbit as it moves slightly closer and farther from Earth.

WHY DOES THE MOON SHOW PHASES?

You have probably noticed that the moon seems to change its shape in a monthly cycle. The apparent shape of the moon, which is determined by the pattern of light and shadow, is called the **phase** of the moon. For example, when the whole side of the moon facing Earth is lighted, we observe the full moon. The gibbous phase occurs when most of the moon appears lighted. When half of the moon appears lighted, it is the quarter moon phase. The crescent phase is a narrow, curved sliver of light. When the whole part of the moon's surface seen from Earth is in shadow, it is known as the new moon. The phase that you see depends on the relative position of the moon with respect to Earth and the sun.

Why is there a monthly cycle of moon phases? This cycle occurs because it takes roughly a month for the moon to orbit Earth. However, the daily rotation of Earth makes the monthly orbiting of the moon more difficult to follow. What you actually observe is the moon rising and setting nearly an hour later each day. Each day for half its cycle the moon moves about 13°away from the Sun's position in the sky. For the other half of the cycle, the moon moves toward the Sun's position in the sky. For this reason, each day or night you see progressively more or less of the moon's lighted surface (the side of the moon facing the sun). The cycle of the moon's phases takes about $29\frac{1}{2}$ days. To fit exactly 12 months into a year, the average calendar month was made a little longer than the full cycle of moon phases.

In a large, darkened room, a friend can help you demonstrate these motions. Due to the dangers posed by a bare light bulb, this should be done under adult supervision. Use a naked light bulb at a distance from you of at least 2–4 meters (7–13 feet) to represent the sun. Your head represents Earth; your eyes represent the position of the observer. A ball can represent the moon. The ball should be much closer to you than the light bulb (the sun). In the most simple representation, stand in one place (although you can turn your head) and observe the lighted part of the ball as your friend moves the ball around (orbits) you. You may want to name each phase as it appears to you. (See Figure 26-6.)

A more realistic, although complicated, demonstration would include you, as Earth, moving in an orbit around the sun while you turn (rotate) 365 times in each orbit. Meanwhile, the moon (the ball held by a friend) needs to move along with you and while orbiting you about 12 times for each time you orbit the more distant light bulb. As you will see, al-

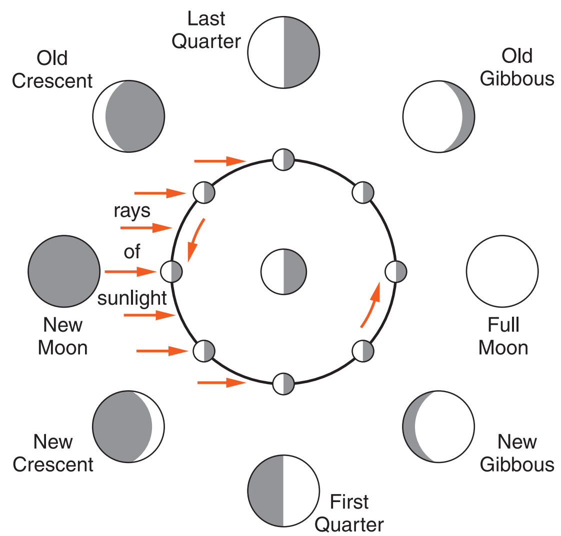

Figure 26-6 The central part of this diagram shows the moon's orbit around Earth as viewed from a position high above the North Pole. The eight outer circles show how a person standing on Earth's surface would see each phase.

though all these motions affect our observations of the Moon, it can be difficult to think about all of them as we observe the changing phases of the Moon.

Earth, Moon, and Sun

Figure 26-6 on page 673 includes two ways of looking at the moon in a single diagram. The central part of this diagram shows the moon orbiting Earth as viewed from a point in space above the North Pole. Notice the arrows showing the orbital motion of the moon as it revolves around Earth. The straight arrows on the left represent rays of light from the sun, which is well outside the diagram to the left.

The eight outer circles show how the moon appears at each position as viewed from Earth. Notice that the first quarter phase at the bottom of the diagram is lit on the left as viewed from above the orbit (inner circle), but lit on the right as viewed from Earth. To understand why the bottom diagram is reversed, turn your book around and look across Earth to the first quarter phase. Then the figure of the moon in its orbit will be lit on the right. Remember that the portion of the moon that is lighted, as well as the side that is lit, depend on the position of the observer.

Earth and Moon

The moon takes about $27\frac{1}{3}$ days to complete one orbit around Earth. However, the cycle of moon phases takes about $29\frac{1}{2}$ days. The reason it takes longer than one revolution of the moon to observe a full cycle of phases is shown in Figure 26-7. Consider Earth and the moon to start at position A. They will be at B $27\frac{1}{3}$ days later. The moon has moved through one complete revolution of 360°. However, to get back to the new moon phase, it must move a little further in its orbit. The reason the cycle of phases takes longer than one revolution of the moon is that Earth is moving in its orbit around the sun.

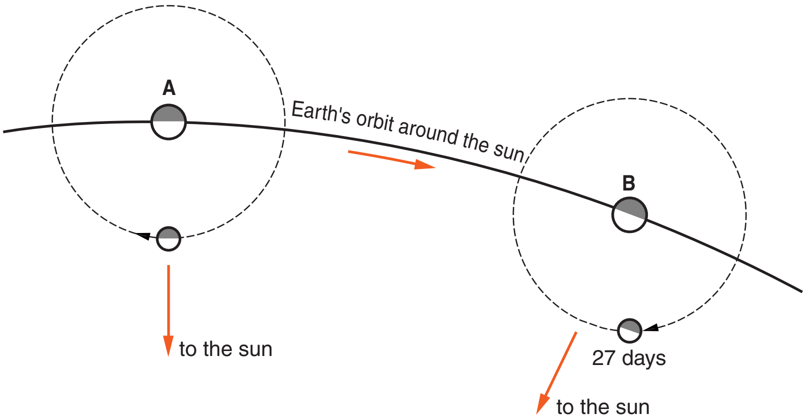

Figure 26-7 Consider Earth and the moon at position A, and 27⅓ days later at position B. The moon has made one complete revolution of 360° from A to B, but the apparent position of the sun has changed. Therefore, the moon must travel another two days to get back to the new moon phase. (This is a view from above the South Pole.)

WHAT IS AN ECLIPSE?

The moon and Earth are not transparent. They cast shadows. Sometimes, the moon's shadow falls on Earth. This may affect the way we see the sun. At other times, Earth's shadow falls on the moon. This may affect the way we see the moon.

Solar Eclipses

As the moon orbits Earth, it sometimes comes between the sun and Earth, casting a shadow on Earth. When one celestial object blocks the light of another, an **eclipse** occurs. If the shadow is cast on Earth's surface, sunlight is blocked. To a person on Earth, the moon is observed to move in front of the sun and then move away. This is called an eclipse of the sun, or solar eclipse. If part of the sun is visible throughout the eclipse, it is called a partial eclipse.

A total eclipse occurs when the sun is completely blocked from view as the region of full shadow passes over Earth as

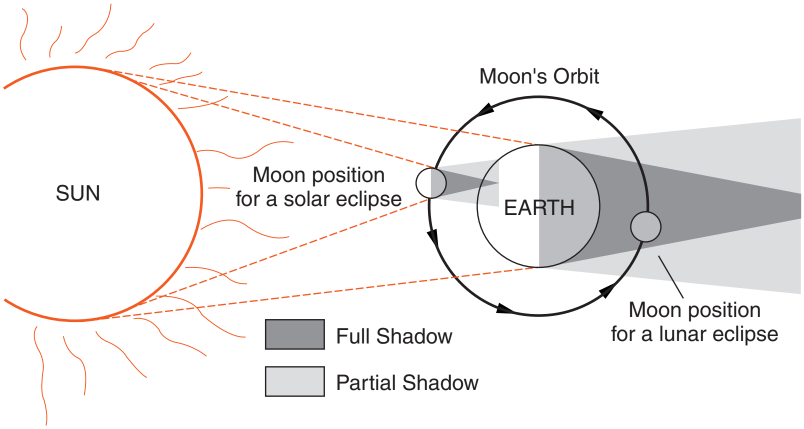

Figure 26-8 A solar eclipse occurs when the moon casts a shadow on Earth's surface. A lunar eclipse happens when the moon passes through Earth's shadow. (Like other diagrams in this chapter, neither object sizes nor distances are to scale.)

shown in Figure 26-8. In a total solar eclipse, the sky becomes much darker than usual and some stars may be visible briefly. A solar eclipse happens only in the new moon phase when the dark half of the moon faces Earth. If a solar eclipse occurs when the moon is relatively far from Earth, the moon may not be cover the entire sun's entire disk. In this type of solar eclipse, the sun may be visible as a ring of light surrounding the dark moon. **(CAUTION: Do not look directly at the sun.)**

Lunar Eclipse

There are also eclipses of the moon, lunar eclipses. An eclipse of the moon occurs when the moon orbits to a position exactly opposite the sun. From Earth, the moon is seen to move into Earth's curved shadow. The moon becomes relatively dark and takes on a coppery-red color from a small amount of light that is refracted through Earth's atmosphere. The eclipse may continue for an hour or more until the moon moves out of Earth's shadow. A lunar eclipse can occur only at the full moon phase because the moon must be on the side of Earth opposite the sun. Figure 26-8 shows the relative position of the moon, Earth, and sun for both solar and lunar eclipses.

Predicting Eclipses

Precise observations of the moon and sun over hundreds of years enable astronomers to predict eclipses with great accuracy. Lunar and solar eclipses occur about once or twice a year. Lunar eclipses are easier to see because they are visible to everyone on the night side of Earth and they may last more than an hour.

Solar eclipses, however, are usually visible only to people located along a narrow path across Earth's surface. An eclipse of the sun usually lasts only a few minutes. If the moon orbits Earth each month, why do you not see eclipses of the sun and moon every month? The reason is that the moon's orbit is tilted at an angle of about 5° from the plane of Earth's orbit around the sun as shown in Figure 26-9. Eclipses occur only when the moon is in the part of its path where the two orbits intersect.

ACTIVITY 26-3 THE NEXT ECLIPSES

Use the Internet to find when the next lunar and solar eclipses will occur. The time is often given in terms of Greenwich Mean Time. Convert the time of the next lunar eclipse into your local time. Where will the next solar eclipse be visible? When will the next solar eclipse be visible in your area?

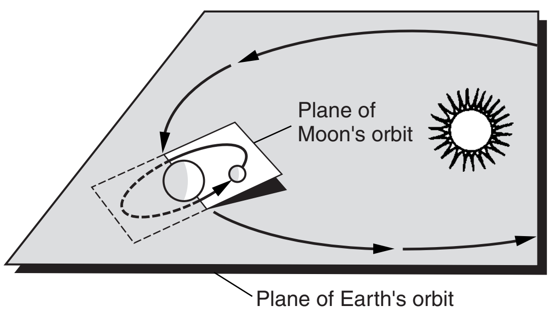

Figure 26-9 The moon's orbit is inclined about 5° from the plane of Earth's orbit. Therefore, the new moon and the full moon are usually above or below the plane of the sun. This explains why eclipses are rare.

ACTIVITY 26-4 MODELING THE MOON'S PHASES

Stand outside in direct sunlight holding a tennis ball. Consider your head to be Earth and the tennis ball to be the moon. Move the tennis ball to each of the eight positions representing the phases of the moon labeled in Figure 26-6.

Then move the tennis ball moon to the positions at which eclipses of the sun and moon would occur. If your head represents Earth, is the moon's size approximately to scale? Is its distance to scale?

Apparent Size of the Sun and Moon

It is a coincidence that as viewed from Earth the moon and sun are each about $\frac{1}{2}°$ in angular diameter. That is, lines drawn from your eye to the sides of the sun or moon are about $\frac{1}{2}°$ of angle apart. In fact, the sun's true diameter is about 400 times the diameter of the moon. However, the moon is much closer to Earth. Consequently, the moon and sun look about the same size to us. The distance from Earth to each of them changes slightly. Sometimes the moon looks slightly larger and sometimes the sun looks slightly larger. Usually this change is not noticeable. However, if a solar eclipse occurs when the sun is relatively close and the moon is relatively far away, the sun can be seen as a ring of light surrounding the dark moon. This is called an annular solar eclipse.

TERMS TO KNOW

ellipse	**gravity**	**phase**	**weight**
focus	**inertia**	**satellite**	