Chapter 22 Origin of Modern Astronomy

Section 1 Early Astronomy

Key Concepts
- How does the geocentric model of the solar system differ from the heliocentric model?
- What were the accomplishments of early astronomers?

Vocabulary
- astronomy
- geocentric
- heliocentric
- retrograde motion
- ellipse
- astronomical unit (AU)

Earth is one of nine planets and many smaller bodies that orbit the sun. The sun is part of a much larger family of perhaps 100 billion stars that make up our galaxy, the Milky Way. There are billions of galaxies in the universe. A few hundred years ago scientists thought that Earth was the center of the universe. In this chapter, you will explore some events that changed the view of Earth’s place in space. You will also examine Earth’s moon.

Ancient Greeks

Astronomy is the science that studies the universe. Astronomy deals with the properties of objects in space and the laws under which the universe operates. The “Golden Age” of early astronomy (600 b.c.–a.d. 150) was centered in Greece. The early Greeks used philosophical arguments to explain natural events. However, they also relied on observations. The Greeks used instruments such as the one in Figure 1. The Greeks developed the basics of geometry and trigonometry. Using these branches of mathematics, they measured the sizes and distances of the sun and the moon.

Figure 1 Early astronomers often used instruments called astrolabes to track the positions of the sun and stars.

The Greeks made many astronomical discoveries. The famous Greek philosopher Aristotle (384–322 b.c.) concluded that Earth is round because it always casts a curved shadow on the moon when it passes between the sun and the moon. Aristotle’s belief that Earth is round was largely abandoned in the Middle Ages. The first successful attempt to establish the size of Earth is credited to Eratosthenes (276–194 b.c.). As shown in Figure 2, Eratosthenes observed the angles of the noonday sun in two Egyptian cities that were roughly north and south of each other—Syene (presently Aswan) and Alexandria. Finding that the angles differed by 7 degrees, or 1/50 of a complete circle, he concluded that the circumference of Earth must be 50 times the distance between these two cities. The cities were 5000 stadia apart, giving him a measurement of 250,000 stadia. Many historians believe the stadia was 157.6 meters. This would make Eratosthenes’ calculation of Earth’s circumference—39,400 kilometers—a measurement very close to the modern circumference of 40,075 kilometers.
Figure 2 This diagram shows the orientation of the sun’s rays at Syene (Aswan) and Alexandria in Egypt on June 21 when Eratosthenes calculated Earth’s circumference.

Probably the greatest of the early Greek astronomers was Hipparchus (second century b.c.), best known for his star catalog. Hipparchus determined the location of almost 850 stars, which he divided into six groups according to their brightness. He measured the length of the year to within minutes of the modern year and developed a method for predicting the times of lunar eclipses to within a few hours.

**Geocentric Model**
The Greeks believed in the geocentric view. They thought that Earth was a sphere that stayed motionless at the center of the universe. In the geocentric model, the moon, sun, and the known planets—Mercury, Venus, Mars, and Jupiter—orbit Earth. Beyond the planets was a transparent, hollow sphere on which the stars traveled daily around Earth. This was called the celestial sphere. To the Greeks, all of the heavenly bodies, except seven, appeared to remain in the same relative position to one another. These seven wanderers included the sun, the moon, Mercury, Venus, Mars, Jupiter, and Saturn. Each was thought to have a circular orbit around Earth. The Greeks were able to explain the apparent movements of all celestial bodies in space by using this model. This model, however, was not correct. Figure 3A on page 616 illustrates the geocentric model.

**Heliocentric Model**
Aristarchus (312–230 b.c.) was the first Greek to believe in a sun-centered, or heliocentric, universe. In the heliocentric model, Earth and the other planets orbit the sun. Aristarchus used geometry to calculate the relative distances from Earth to the sun and from Earth to the moon. He later used these distances to calculate the size of the sun and the moon. But Aristarchus came up with measurements that were much too small. However, he did learn that the sun was many times more distant than the moon and many times larger than Earth. Though there was evidence to support the heliocentric model, as shown in Figure 3B, the Earth-centered view, shown in Figure 3A, dominated Western thought for nearly 2000 years.

**Ptolemaic System**
Much of our knowledge of Greek astronomy comes from Claudius Ptolemy. In a 13-volume work published in a.d. 141, Ptolemy presented a model of the universe that was called the Ptolemaic system. It accounted for the
movements of the planets. The precision with which his model was able to predict the motion of the planets allowed it to go unchallenged for nearly 13 centuries. Just like the Greeks, Ptolemy's model had the planets moving in circular orbits around a motionless Earth. However, the motion of the planets against the background of stars seemed odd. Each planet, if watched night after night, moves slightly eastward among the stars. Periodically, each planet appears to stop, reverse direction for a time, and then resume an eastward motion. The apparent westward drift is called retrograde motion and is diagrammed in Figure 4 on page 617. This rather odd apparent motion results from the combination of the motion of Earth and the planet’s own motion around the sun, as shown in Figure 4.

Figure 4 Retrograde Motion
When viewed from Earth, Mars moves eastward among the stars each day. Then periodically it appears to stop and reverse direction. This apparent movement, called retrograde motion, occurs because Earth has a faster orbital speed than Mars and overtakes it. It is difficult to accurately represent retrograde motion by using the Earth-centered model. Even though Ptolemy used the wrong model, he was able to account for the planets’ motions.

The Birth of Modern Astronomy
The development of modern astronomy involved a break from previous philosophical and religious views. Scientists began to discover a universe governed by natural laws. We will examine the work of five noted scientists: Nicolaus Copernicus, Tycho Brahe, Johannes Kepler, Galileo Galilei, and Sir Isaac Newton.

Nicolaus Copernicus
For almost 13 centuries after the time of Ptolemy, very few astronomical advances were made in Europe. The first great astronomer to emerge after the Middle Ages was Nicolaus Copernicus (1473–1543) from Poland. Copernicus became convinced that Earth is a planet, just like the other five planets that were known. The daily motions of the heavens, he reasoned, could be better explained by a rotating Earth. Copernicus concluded that Earth is a planet. He proposed a model of the solar system with the sun at the center. This was a major break from the ancient idea that a motionless Earth lies at the center. Copernicus used circles, which were considered to be the perfect geometric shape, to represent the orbits of the planets. However, the planets seemed to stray from their predicted positions.

Tycho Brahe
Tycho Brahe (1546–1601) was born of Danish nobility three years after the death of Copernicus. Brahe became interested in astronomy while viewing a solar eclipse that had been predicted by astronomers. He persuaded King Frederick II to build an observatory near Copenhagen. The telescope had not yet been invented. At the observatory, Brahe designed and built instruments, such as the angle-measuring device shown in Figure 5. He used these instruments for 20 years to measure the locations of the heavenly bodies. Brahe’s observations, especially of Mars, were far more precise than any made previously. In the last year of his life, Brahe found an able assistant, Johannes Kepler. Kepler kept most of Brahe’s observations and put them to exceptional use.
Johannes Kepler

Copernicus ushered out the old astronomy, and Johannes Kepler (1571–1630) ushered in the new. Kepler had a good mathematical mind and a strong faith in the accuracy of Brahe’s work. Kepler discovered three laws of planetary motion. The first two laws resulted from his inability to fit Brahe’s observations of Mars to a circular orbit. Kepler discovered that the orbit of Mars around the sun is not a perfect circle. Instead, it is an oval-shaped path called an ellipse. About the same time, he realized that the speed of Mars in its orbit changes in a predictable way. As Mars approaches the sun, it speeds up. As it moves away from the sun, it slows down.

After decades of work, Kepler summarized three laws of planetary motion:

1. The path of each planet around the sun is an ellipse, with the sun at one focus. The other focus is symmetrically located at the opposite end of the ellipse.

2. Each planet revolves so that an imaginary line connecting it to the sun sweeps over equal areas in equal time intervals, as shown in Figure 6. If a planet is to sweep equal areas in the same amount of time, it must travel more rapidly when it is nearer the sun and more slowly when it is farther from the sun.

3. The square of the length of time it takes a planet to orbit the sun (orbital period) is proportional to the cube of its mean distance to the sun.

In its simplest form, the orbital period of revolution is measured in Earth years. The planet’s distance to the sun is expressed in astronomical units. The astronomical unit (AU) is the average distance between Earth and the sun. It is about 150 million kilometers.

Using these units, Kepler’s third law states that the planet’s orbital period squared is equal to its mean solar distance cubed ($P^2 = a^3$). Therefore, the solar distances of the planets can be calculated when their periods of
revolution are known. For example, Mars has a period of 1.88 years, which squared equals 3.54. The cube root of 3.54 is 1.52, and that is the distance to Mars in astronomical units shown in Table 1.

### Table 1: Period of Revolution and Solar Distances of Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Solar Distance (AU)*</th>
<th>Period (Earth years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.39</td>
<td>0.24</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>0.62</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mars</td>
<td>1.52</td>
<td>1.88</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.20</td>
<td>11.86</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.54</td>
<td>29.46</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.18</td>
<td>84.01</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.06</td>
<td>164.80</td>
</tr>
<tr>
<td>Pluto</td>
<td>39.44</td>
<td>247.70</td>
</tr>
</tbody>
</table>

*AU — astronomical unit.

**Galileo Galilei**

Galileo Galilei (1564–1642) was the greatest Italian scientist of the Renaissance. Galileo’s most important contributions were his descriptions of the behavior of moving objects. All astronomical discoveries before his time were made without the aid of a telescope. In 1609, Galileo heard that a Dutch lens maker had devised a system of lenses that magnified objects. Apparently without ever seeing a telescope, Galileo constructed his own. It magnified distant objects to three times the size seen by the unaided eye.

Using the telescope, Galileo was able to view the universe in a new way. He made many important discoveries that supported Copernicus’s view of the universe, such as the following:

1. The discovery of four satellites, or moons, orbiting Jupiter. This proved that the old idea of Earth being the only center of motion in the universe was wrong. Here, plainly visible, was another center of motion—Jupiter. People who opposed the sun-centered system said that the moon would be left behind if Earth really revolved around the sun. Galileo’s discovery disproved this argument.

2. The discovery that the planets are circular disks, not just points of light, as was previously thought. This showed that the planets must be Earth-like.

3. The discovery that Venus has phases just like the moon. So Venus orbits its source of light—the sun. Galileo saw that Venus appears smallest when it is in full phase and therefore farthest from Earth, as shown in Figure 7.

![Figure 7: Relating Cause And Effect](image)

In the geocentric model, which phase of Venus would be visible from Earth?

4. The discovery that the moon’s surface was not smooth. Galileo saw mountains, craters, and plains. He thought the plains might be bodies of water. This idea was also believed by others, as we can tell from the names given to these features (Sea of Tranquility, Sea of Storms, and so forth).

5. The discovery that the sun had sunspots, or dark regions. Galileo tracked the movement of these spots and estimated the rotational period of the sun as just under a month.

**Sir Isaac Newton**

Sir Isaac Newton (1642–1727) was born in the year of Galileo’s death. See Figure 8. Many scientists had attempted to explain the forces involved in planetary motion. Kepler believed that some force pushed the planets along in their orbits. Galileo correctly reasoned that no force is required to keep an object in motion. And he
proposed that a moving object will continue to move at a constant speed and in a straight line. This concept is called inertia.

Figure 8 Sir Isaac Newton

The problem, then, was not to explain the force that keeps the planets moving but rather to determine the force that keeps them from going in a straight line out into space. At the age of 23, Newton described a force that extends from Earth into space and holds the moon in orbit around Earth. Although others had theorized the existence of such a force, Newton was the first to formulate and test the law of universal gravitation.

Universal Gravitation

According to Newton, every body in the universe attracts every other body with a force that is directly proportional to their masses and inversely proportional to the square of the distance between their centers of mass. The gravitational force decreases with distance, so that two objects 3 kilometers apart have $3^2$, or 9, times less gravitational attraction than if the same objects were 1 kilometer apart.

The law of universal gravitation also states that the greater the mass of the object, the greater is its gravitational force. For example, the mass of the moon creates a gravitational force strong enough to cause ocean tides on Earth. But the tiny mass of a satellite has no measurable effect on Earth. The mass of an object is a measure of the total amount of matter it contains. But more often mass is measured by finding how much an object resists any effort to change its state of motion.

Often we confuse the concept of mass with weight. Weight is the force of gravity acting upon an object. Weight is properly expressed in newtons (N). Therefore, weight varies when gravitational forces change. See Figure 9.

Figure 9 Weight is the force of gravity acting on an object. A An astronaut with a mass of 88 kg weighs 863 N on Earth. B An astronaut with a mass of 88 kg weighs 141 N on the moon. Calculating If the same astronaut stood on Mars where the acceleration due to gravity is about 3.7 m/s², how much would the astronaut weigh?

Newton proved that the force of gravity, combined with the tendency of a planet to remain in straight-line motion, results in the elliptical orbits that Kepler discovered. Earth, for example, moves forward in its orbit about 30 kilometers each second. During the same second, the force of gravity pulls it toward the sun about 0.5 centimeter. Newton concluded that it is the combination of Earth’s forward motion and its “falling” motion that defines its orbit. As Figure 10 shows, if gravity were somehow eliminated, Earth would move in a straight line out into space. If Earth’s forward motion suddenly stopped, gravity would pull it directly toward the sun.
Without the influence of gravity, planets would move in a straight line out into space.

Newton used the law of universal gravitation to redefine Kepler’s third law, which states the relationship between the orbital periods of the planets and their solar distances. When restated, Kepler’s third law takes into account the masses of the bodies involved and provides a method for determining the mass of a body when the orbit of one of its satellites is known.

Section 2 The Earth-Moon-Sun System

Key Concepts
- In what ways does Earth move?
- What causes the phases of the moon?
- Why are eclipses relatively rare events?

Vocabulary
- rotation
- revolution
- precession
- perihelion
- aphelion
- perigee
- apogee
- phases of the moon
- solar eclipse
- lunar eclipse

If you gaze away from the city lights on a clear night, it will seem that the stars produce a spherical shell surrounding Earth. This impression seems so real that it is easy to understand why many early Greeks regarded the stars as being fixed to a solid, celestial sphere. People have always been fascinated by the changing positions of the sun and moon in the sky. Prehistoric people, for example, built observatories. The structure known as Stonehenge, shown in Figure 11, was probably an attempt at better solar predictions. At the beginning of summer in the Northern Hemisphere (the summer solstice on June 21 or 22), the rising sun comes up directly above the heel stone of Stonehenge. Besides keeping this calendar, Stonehenge may also have provided a method of determining eclipses. In this section, you’ll learn more about the movements of bodies in space that cause events such as eclipses.

Figure 11 On the summer solstice, the sun can be observed rising above the heel stone of Stonehenge, an ancient observatory in England.
Motions of Earth
The two main motions of Earth are rotation and revolution. **Rotation** is the turning, or spinning, of a body on its axis. **Revolution** is the motion of a body, such as a planet or moon, along a path around some point in space. For example, Earth revolves around the sun, and the moon revolves around Earth. Earth also has another very slow motion known as **precession**, which is the slight movement, over a period of 26,000 years, of Earth’s axis.

**Rotation**
The main results of Earth’s rotation are day and night. Earth’s rotation has become a standard method of measuring time because it is so dependable and easy to use. Each rotation equals about 24 hours. You may be surprised to learn that we can measure Earth’s rotation in two ways, making two kinds of days. Most familiar is the mean solar day, the time interval from one noon to the next, which averages about 24 hours. Noon is when the sun has reached its zenith, or highest point in the sky.

The sidereal day, on the other hand, is the time it takes for Earth to make one complete rotation (360 degrees) with respect to a star other than our sun. The sidereal day is measured by the time required for a star to reappear at the identical position in the sky where it was observed the day before. The sidereal day has a period of 23 hours, 56 minutes, and 4 seconds (measured in solar time), which is almost 4 minutes shorter than the mean solar day. This difference results because the direction to distant stars barely changes because of Earth’s slow revolution along its orbit. The direction to the sun, on the other hand, changes by almost 1 degree each day. This difference is shown in Figure 12.

![Figure 12 Sidereal Day](https://via.placeholder.com/150)

- **Figure 12 Sidereal Day** It takes Earth 23 hours and 56 minutes to make one rotation with respect to the stars (sidereal day). However, after Earth has completed one sidereal day, point Y has not yet returned to the “noon position” with respect to the sun. Earth has to rotate another 4 minutes to complete the solar day.

Why do we use the mean solar day instead of the sidereal day as a measurement of our day? In sidereal time, “noon” occurs four minutes earlier each day. Therefore, after six months, “noon” occurs at “midnight.” Astronomers use sidereal time because the stars appear in the same position in the sky every 24 sidereal hours. Usually, an observatory will begin its sidereal day when the position of the spring equinox is directly overhead.

**Revolution**
Earth revolves around the sun in an elliptical orbit at an average speed of 107,000 kilometers per hour. Its average distance from the sun is 150 million kilometers. But because its orbit is an ellipse, Earth’s distance from the sun varies. At **perihelion**, Earth is closest to the sun—about 147 million kilometers away. Perihelion occurs about January 3 each year. At **aphelion**, Earth is farthest from the sun—about 152 million kilometers away. Aphelion occurs about July 4. So Earth is farthest from the sun in July and closest to the sun in January.

Because of Earth’s annual movement around the sun, each day the sun appears to be displaced among the constellations at a distance equal to about twice its width, or 1 degree. The apparent annual path of the sun against the backdrop of the celestial sphere is called the ecliptic, as shown in Figure 13. Generally, the planets and the moon travel in nearly the same plane as Earth. So their paths on the celestial sphere lie near the ecliptic.
Earth’s Axis and Seasons
The imaginary plane that connects Earth’s orbit with the celestial sphere is called the plane of the ecliptic. From the reference plane, Earth’s axis of rotation is tilted about 23.5 degrees. Because of Earth’s tilt, the apparent path of the sun and the celestial equator intersect each other at an angle of 23.5 degrees. This angle is very important to Earth’s inhabitants. Because of the inclination of Earth’s axis to the plane of the ecliptic, Earth has its yearly cycle of seasons.

When the apparent position of the sun is plotted on the celestial sphere over a period of a year’s time, its path intersects the celestial equator at two points. From a Northern Hemisphere point of view, these intersections are called the spring equinox (March 20 or 21) and autumn equinox (September 22 or 23). On June 21 or 22, the date of the summer solstice, the sun appears 23.5 degrees north of the celestial equator. Six months later, on December 21–22, the date of the winter solstice, the sun appears 23.5 degrees south of the celestial equator.

Precession
A third and very slow movement of Earth is called precession. Earth’s axis maintains approximately the same angle of tilt. But the direction in which the axis points continually changes. As a result, the axis traces a circle on the sky. This movement is very similar to the wobble of a spinning top, as shown in Figure 14A. At the present time, the axis points toward the bright star Polaris. In the year 14,000, it will point toward the bright star Vega, which will then become the North Star, as shown in Figure 14B. The period of precession is 26,000 years. By the year 28,000, Polaris will once again be the North Star.

Precession has only a minor effect on the seasons, because the angle of tilt changes only slightly. It does, however, cause the positions of the seasons (equinox and solstice) to move slightly each year among the stars.
Earth-Sun Motion
In addition to its own movements, Earth accompanies the sun as the entire solar system speeds in the direction of the bright star Vega at 20 kilometers per second. Also, the sun, like other nearby stars, revolves around the galaxy. This trip takes 230 million years to traverse at speeds approaching 250 kilometers per second. The galaxies themselves are also in motion. Earth is presently approaching one of its nearest galactic neighbors, the Great Galaxy in Andromeda. The motions of Earth are many and complex, and its speed in space is very great.

Motions of the Earth-Moon System
Earth has one natural satellite, the moon. In addition to accompanying Earth in its annual trip around the sun, our moon orbits Earth within a period of about one month. When viewed from above the North Pole, the direction of this motion is counterclockwise. Because the moon’s orbit is elliptical, its distance to Earth varies by about 6 percent, averaging 384,401 kilometers. At a point known as perigee, the moon is closest to Earth. At a point known as apogee, the moon is farthest from Earth. The motions of the Earth-moon system constantly change the relative positions of the sun, Earth, and moon. This results in changes in the appearance of the moon, as you’ll read about next.

Phases of the Moon
The first astronomical event to be understood was the regular cycle of the phases of the moon. On a monthly basis, we observe the phases of the moon as a change in the amount of the moon that appears lit. Look at the new moon shown in Figure 15A. About two days after the new moon, a thin sliver (crescent phase) appears low in the western sky just after sunset. During the following week, the lighted portion of the moon visible from Earth increases (waxing) to a half circle (first-quarter phase) and can be seen from about noon to midnight. In another week, the complete disk (full-moon phase) can be seen rising in the east as the sun is sinking in the west. During the next two weeks, the percentage of the moon that can be seen steadily declines (waning), until the moon disappears altogether (new-moon phase). The cycle soon begins again with the reappearance of the crescent moon.

Figure 15 Phases of the Moon A The outer figures show the phases as seen from Earth. B Compare these photographs with the diagram.
Lunar phases are a result of the motion of the moon and the sunlight that is reflected from its surface. See Figure 15B. Half of the moon is illuminated at all times. But to an observer on Earth, the percentage of the bright side that is visible depends on the location of the moon with respect to the sun and Earth. When the moon lies between the sun and Earth, none of its bright side faces Earth. When the moon lies on the side of Earth opposite the sun, all of its lighted side faces Earth. So we see the full moon. At all positions between the new moon and the full moon, a part of the moon’s lit side is visible from Earth.

**Lunar Motions**

The cycle of the moon through its phases requires 29 ½ days, a time span called the synodic month. This cycle was the basis for the first Roman calendar. However, this is the apparent period of the moon’s revolution around Earth and not the true period, which takes only 27 ⅓ days and is known as the sidereal month. The reason for the difference of nearly two days each cycle is shown in Figure 16. Note that as the moon orbits Earth, the Earth-moon system also moves in an orbit around the sun. Even after the moon has made a complete revolution around Earth, it has not yet reached its starting position, which was directly between the sun and Earth (new-moon phase). The additional motion to reach the starting point takes another two days.

![Figure 16 Lunar Motion](chart.jpg)

An interesting fact about the motions of the moon is that the moon’s period of rotation about its axis and its revolution around Earth are the same. They are both 27 ⅓ days. Because of this, the same side of the moon always faces Earth. All of the crewed Apollo missions took place on the side of the moon facing Earth. Only orbiting satellites and astronauts have seen the “back” side of the moon.

Because the moon rotates on its axis only once every 27 ⅓ days, any location on its surface experiences periods of daylight and darkness lasting about two weeks. This, along with the absence of an atmosphere, accounts for the high surface temperature of 127°C on the day side of the moon and the low surface temperature of −173°C on its night side.

Q Why do we sometimes see the moon in daytime?
A During phases of the lunar cycle other than the full moon, the moon and sun are not directly opposite each other. This makes it possible to see the moon during daylight hours.

**Eclipses**

Along with understanding the moon’s phases, the early Greeks also realized that eclipses are simply shadow effects. When the moon moves in a line directly between Earth and the sun, it casts a dark shadow on Earth. This produces a solar eclipse. This situation occurs during new-moon phases. The moon is eclipsed when it moves within Earth’s shadow, producing a lunar eclipse. This situation occurs during full-moon phases. Figure 17 illustrates solar and lunar eclipses.
During a total lunar eclipse, Earth’s circular shadow can be seen moving slowly across the disk of the full moon. When totally eclipsed, the moon is completely within Earth’s shadow, but it is still visible as a coppery disk. This happens because Earth’s atmosphere bends and transmits some long-wavelength light (red) into its shadow. A total eclipse of the moon can last up to four hours and is visible to anyone on the side of Earth facing the moon. During a total solar eclipse, the moon casts a circular shadow that is never wider than 275 kilometers, about the size of South Carolina. Anyone observing in this region will see the moon slowly block the sun from view and the sky darken. When the eclipse is almost complete, the temperature sharply drops a few degrees. The solar disk is completely blocked for seven minutes at the most. This happens because the moon’s shadow is so small. Then one edge reappears.

When the eclipse is complete, the dark moon is seen covering the complete solar disk. Only the sun’s brilliant white outer atmosphere is visible. Total solar eclipses are visible only to people in the dark part of the moon’s shadow known as the umbra. A partial eclipse is seen by those in the light portion of the shadow, known as the penumbra.

Partial solar eclipses are more common in the polar regions. In this zone, the penumbra covers the dark umbra of the moon’s shadow, just missing Earth. A total solar eclipse is a rare event at any location. The next one that will be visible from the United States will take place on August 21, 2017.
Section 3  Earth’s Moon

Key Concepts
- What processes create surface features on the moon?
- How did the moon form?

Vocabulary
- crater
- ray
- mare
- rille
- lunar regolith

Earth now has hundreds of satellites. Only one natural satellite, the moon, accompanies us on our annual journey around the sun. Other planets have moons. But our planet-satellite system is unusual in the solar system, because Earth’s moon is unusually large compared to its parent planet. The diameter of the moon is 3475 kilometers, about one-fourth of Earth’s 12,756 kilometers.

Much of what we know about the moon, shown in Figure 18, comes from data gathered by the Apollo moon missions. Six Apollo spacecraft landed on the moon between 1969 and 1972. Uncrewed spacecraft such as the Lunar Prospector have also explored the moon’s surface. From calculation of the moon’s mass, we know that its density is 3.3 times that of water. This density is comparable to that of mantle rocks on Earth. But it is considerably less than Earth’s average density, which is 5.5 times that of water. Geologists have suggested that this difference can be accounted for if the moon’s iron core is small. The gravitational attraction at the lunar surface is one-sixth of that experienced on Earth’s surface. (A 150-pound person on Earth weighs only 25 pounds on the moon). This difference allows an astronaut to carry a heavy life-support system easily. An astronaut on the moon could jump six times higher than on Earth.

The Lunar Surface
When Galileo first pointed his telescope toward the moon, he saw two different types of landscape—dark lowlands and bright highlands. Because the dark regions resembled seas on Earth, they were later named maria, which comes from the Latin word for sea. Today we know that the moon has no atmosphere or water. Therefore, the moon doesn’t have the weathering and erosion that continually change Earth’s surface. Also, tectonic forces aren’t active on the moon, therefore volcanic eruptions no longer occur. However, because the moon is unprotected by an atmosphere, a different kind of erosion occurs. Tiny particles from space continually bombard its surface and gradually smooth out the landscape. Moon rocks become slightly rounded on top after a long time at the lunar surface. Even so, it is unlikely that the moon has changed very much in the last 3 billion years, except for a few craters.
Craters
The most obvious features of the lunar surface are **craters**, which are round depressions in the surface of the moon. There are many craters on the moon. The moon even has craters within craters! The larger craters are about 250 kilometers in diameter, about the width of Indiana. Most craters were produced by the impact of rapidly moving debris.

By contrast, Earth has only about a dozen easily recognized impact craters. Friction with Earth’s atmosphere burns up small debris before it reaches the ground. Evidence for most of the craters that formed in Earth’s history has been destroyed by erosion or tectonic processes.

The formation of an impact crater is modeled in Figure 19. Upon impact, the colliding object compresses the material it strikes. This process is similar to the splash that occurs when a rock is dropped into water. A central peak forms after the impact.

![Figure 19](image)

*Figure 19 The energy of the rapidly moving meteoroid is transformed into heat energy. Rock compresses, then quickly rebounds. The rebounding rock causes debris to be ejected from the crater.*

Most of the ejected material lands near the crater, building a rim around it. The heat generated by the impact is enough to melt rock. Astronauts have brought back samples of glass and rock formed when fragments and dust were welded together by the impact.

A meteoroid only 3 meters in diameter can blast out a 150-meterwide crater. A few of the large craters, such as those named Kepler and Copernicus, formed from the impact of bodies 1 kilometer or more in diameter. These two large craters are thought to be relatively young because of the bright **rays**, or splash marks that radiate outward for hundreds of kilometers.

Highlands
Most of the lunar surface is made up of densely pitted, light-colored areas known as highlands. In fact, highlands cover the surface of the far side of the moon. The same side of the moon always faces Earth. Within the highland regions are mountain ranges. The highest lunar peaks reach elevations of almost 8 kilometers. This is only 1 kilometer lower than Mount Everest. Figure 20 shows highlands and other features of the moon.
Figure 20 Major topographic features on the moon’s surface include craters, maria, and highlands. Identifying Where are rilles located?

Maria
The dark, relatively smooth area on the moon’s surface is called a mare (plural: maria). Maria, ancient beds of basaltic lava, originated when asteroids punctured the lunar surface, letting magma bleed out. Apparently the craters were flooded with layer upon layer of very fluid basaltic lava somewhat resembling the Columbia Plateau in the northwestern United States. The lava flows are often over 30 meters thick. The total thickness of the material that fills the maria could reach thousands of meters.

Long channels called rilles are associated with maria. Rilles look somewhat similar to valleys or trenches. Rilles may be the remnants of ancient lava flows.

Regolith
All lunar terrains are mantled with a layer of gray debris derived from a few billion years of bombardment from meteorites. This soil-like layer, called lunar regolith, is composed of igneous rocks, glass beads, and fine lunar dust. In the maria that have been explored by Apollo astronauts, the lunar regolith is just over 3 meters thick.

Lunar History
The moon is our nearest planetary neighbor. Although astronauts have walked on its surface, much is still unknown about its origin. The most widely accepted model for the origin of the moon is that when the solar system was forming, a body the size of Mars impacted Earth. The impact, shown in Figure 21, would have liquefied Earth’s surface and ejected huge quantities of crustal and mantle rock from an infant Earth. A portion of this ejected debris would have entered an orbit around Earth where it combined to form the moon.

Figure 21 The moon may have formed when a large object collided with Earth. The resulting debris was ejected into space. The debris began orbiting around Earth and eventually united to form the moon.
The giant-impact hypothesis is consistent with other facts known about the moon. The ejected material would have been mostly iron-poor mantle and crustal rocks. These would account for the lack of a sizable iron core on the moon. The ejected material would have remained in orbit long enough to have lost the water that the moon lacks. Despite this supporting evidence, some questions remain unanswered.

Geologists have worked out the basic details of the moon’s later history. One of their methods is to observe variations in crater density (the number of craters per unit area). The greater the crater density, the older the surface must be. From such evidence, scientists concluded that the moon evolved in three phases—the original crust (highlands), maria basins, and rayed craters.

During its early history, the moon was continually impacted as it swept up debris. This continuous attack, combined with radioactive decay, generated enough heat to melt the moon’s outer shell and possibly the interior as well. Remnants of this original crust occupy the densely cratered highlands. These highlands have been estimated to be as much as 4.5 billion years old, about the same age as Earth.

One important event in the moon’s evolution was the formation of maria basins. Radiometric dating of the maria basalts puts their age between 3.2 billion and 3.8 billion years, about a billion years younger than the initial crust. In places, the lava flows overlap the highlands, which also explains the younger age of the maria deposits. The last prominent features to form were the rayed craters. Material ejected from these young depressions is clearly seen covering the surface of the maria and many older rayless craters. Even a relatively young crater like Copernicus, shown in Figure 22, must be millions of years old. If it had formed on Earth, erosional forces would have erased it long ago. If photographs of the moon taken several hundreds of millions of years ago were available, they would show that the moon has changed little. The moon is an inactive body wandering through space and time.

![Figure 22 Rayed craters such as Copernicus were the last major features to form on the moon.](image-url)
Foucault’s Experiment

Earth rotates on its axis once each day to produce periods of daylight and darkness. However, day and night and the apparent motions of the stars can be accounted for equally well by a sun and celestial sphere that revolve around a stationary Earth. Copernicus realized that a rotating Earth greatly simplified the existing model of the universe. He was unable, however, to prove that Earth rotates. The first real proof was presented 300 years after his death by the French physicist Jean Foucault.

The Swinging Pendulum

In 1851, Foucault used a free-swinging pendulum to demonstrate that Earth does, in fact, turn on its axis. To picture Foucault’s experiment, imagine a large pendulum swinging over the North Pole, as shown in the illustration on this page. Keep in mind that once a pendulum is put into motion, it continues swinging in the same plane unless acted upon by some outside force. Assume that a sharp point is attached to the bottom of this pendulum, marking the snow as it swings. If we were to observe the marks made by the point, we would see that the pendulum is slowly but continually changing position. At the end of 24 hours, the pendulum would have returned to its starting position.

Evidence of Earth’s Rotation

No outside force acted on the pendulum to change its position. So what we observed must have been Earth rotating beneath the pendulum. Foucault conducted a similar experiment when he suspended a long pendulum from the dome of the Pantheon in Paris. Today, Foucault pendulums can be found in some museums to re-create this famous scientific experiment.