



**RIVUXG** Gravity is the only universal force of attraction in the universe. Despite the magnificent solitude that astronaut Bruce McCandless II experienced floating a football-field length from the space shuttle *Challenger*, he was being held in orbit around Earth with almost the same amount of gravitational attraction that our planet has on each of us. He is falling toward Earth but continually missing it. Why? (STS-41B, NASA)

# Gravitation and the Motion of the Planets

## WHAT DO YOU THINK?

- 1 What makes a theory scientific?
- 2 What is the shape of Earth's orbit around the Sun?
- 3 Do the planets orbit the Sun at constant speeds?
- 4 Do all of the planets orbit the Sun at the same speed?
- 5 How does an object's mass differ when measured on Earth and on the Moon?
- 6 Do astronauts orbiting Earth feel the force of gravity from our planet?

*Answers to these questions appear in the text beside the corresponding numbers in the margins and at the end of the chapter.*

We begin this chapter by examining the nature of science, scientific investigation, and scientific inquiry. With the process of scientific investigation in mind, we explore how scientists came to discover that Earth and the other planets orbit the Sun. Then, in the spirit of scientific inquiry, we ask and answer the question “why do they have these orbits?”

### In this chapter you will discover

- what makes a theory scientific
- the scientific discoveries that revealed that Earth is not at the center of the universe, as previously believed
- Copernicus’s argument that the planets orbit the Sun
- why the direction of motion of each planet on the celestial sphere sometimes changes
- that Kepler’s determination of the shapes and other properties of planetary orbits depended on the careful observations of his mentor Tycho Brahe
- how Isaac Newton formulated an equation to describe the force of gravity and how he thereby explained why the planets and moons remain in orbit

## SCIENCE: KEY TO COMPREHENDING THE COSMOS

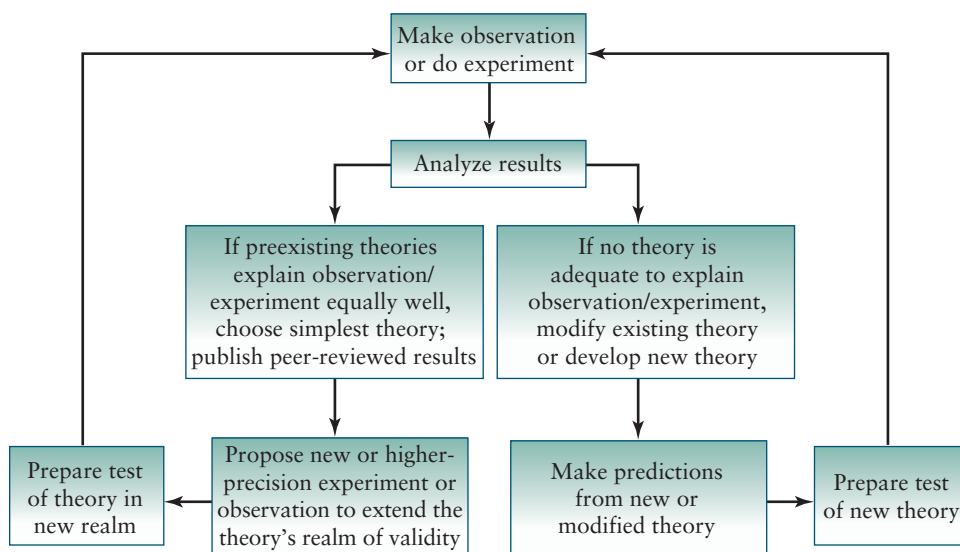
The groundwork for modern science was laid down by Greek “natural philosophers” beginning about 2500 years ago, when Pythagoras and his followers began using mathematics to describe natural phenomena. These Greek ideas, translated into Arabic, were rediscovered in the West in the seventeenth century. They led to the development of the scientific method of examining, understanding, and predicting how things work.

### 2-1 Science is both a body of knowledge and a process of learning about nature

Science is actually two related things. First, it is a body of knowledge that we acquire through observations, experiments, and mathematical calculations. The fact the planets orbit the Sun, along with equations that describe and predict these motions, are examples of that knowledge.

Second, science is a process for gaining more knowledge and deeper understanding of nature in a way that ensures that the information can be tested and thereby accepted by everyone. Science as a process is also called the **scientific method**, which describes how scientists ideally go about observing, explaining, and predicting physical reality.

The scientific method (Figure 2-1) can begin in a variety of places, but most often it starts with people making observations or doing experiments. Observations of planetary orbits provided to Johannes Kepler enabled him to derive Kepler’s laws, which are presented later in this chapter. These equations then accurately predicted the paths of other bodies in the solar system, such as moons orbiting planets. Understanding why Kepler’s laws are correct required understanding the force of gravity. English physicists Robert Hooke and Isaac Newton proposed that the force of gravity decreases inversely with the square of the distance between any two



**Figure 2-1 The Scientific Method** This flowchart shows the basic steps in the process by which scientists study nature and develop new scientific theories. Different scientists start at different places on this chart, including making observations or doing experiments, creating or modifying scientific theories, or making predictions from theories. Anyone interested in some aspect of science and willing to learn the tools of the trade can participate in the adventure.

objects, such as Earth and the Moon. (This means, for example, that if you double the distance, the force of gravity is four times weaker.) Newton went on to derive Kepler's laws based on this assumption about the force of gravity. The force of gravity was thus added to the body of scientific knowledge and was then used to explain existing observations and to make predictions about previously unobserved motions.

If a theory exists that purports to explain previous observations, new observations or experimental results are then compared with the predictions of the theory. If the new data and old theory are not consistent, then a *hypothesis* that modifies or replaces the existing explanation is proposed. (If no theory explains observations or experimental results, a new hypothesis is proposed to explain them.) Hypotheses on related topics that make accurate predictions are incorporated together as a **scientific theory** (often just called a **theory**). Scientific theories are presented in the form of mathematical equations and accompanying explanations.

An interesting example of beginning a scientific inquiry with equations, rather than observations or experiments, is the discovery of a particle called the Higgs boson. This particle is what causes matter to have mass, which in turn allows matter to interact gravitationally, among other things. In 1964, Scottish physicist Peter Higgs, along with other scientists, predicted the existence of this particle based on powerful equations that describe the properties of matter. Based on this prediction, experiments were run to discover the Higgs boson. Scientists believe that it was observed in July 2012, at the Large Hadron Collider in Switzerland.

In everyday conversation, a theory is an idea based on common sense, intuition, or deep-seated personal beliefs. Such theories neither originate in equations nor do they usually lead to rigorous predictions. The word *theory* in science has a very different meaning. A scientific theory is an explanation of observations or experimental results that can be described quantitatively (that is, in terms of equations) and tested formally. The mathematical description used in a scientific theory is considered a **model** of the real system. For example, Newton's *theory* (or, in earlier usage, *law*) of gravitation is written as an equation that predicts how bodies attract each other. (The word *gravity* is often used as shorthand for *gravitation*, and both are used in this book.)

**1** As just noted, to be considered scientific, a theory must make *testable* predictions that can be verified by making new observations or doing new experiments. Testing is a crucial aspect of the scientific method, which also requires that the theory accurately forecast the results of new observations in its realm of validity. Newton's law of gravitation predicts that the Sun's gravitational force makes the planets move in elliptical orbits, and it predicts how long it should take each planet to orbit the

Sun. As we will see shortly, observations have confirmed most of these predictions.

For a theory to be considered scientific, it must also be potentially possible to disprove it. For example, Newton's law of gravitation can be tested and potentially disproven by observations and thus qualifies as a scientific theory. The idea that Earth was created in 6 days cannot be tested, much less disproved. It is not a scientific theory but rather a matter of faith.

One important theme in science is to look for patterns that allow seemingly unrelated events or activities to be explained by one theory. For example, Newton observed that the Moon's motion around Earth had the same behavior as the motion of a flying cannonball. Indeed, if you fired a cannonball fast enough, it would orbit Earth just as the Moon does. He hypothesized that they were both responding to Earth's gravitational attraction, which led to his successfully applying the same equations to describe their motions. The motion of the planets around the Sun, he found, could also be described by the same equations. One theory. Three applications. Very satisfying! It is worth noting that Newton's theory of gravity has since been applied successfully to myriad other situations.

Science strives to explain as many things as possible with as few theories as possible. As another example, we see billions upon billions of objects in the universe. It would be virtually impossible to study all of them separately so that we could come up with detailed descriptions of each one. Fortunately, individual theories explaining each object are not necessary. Scientists overcome this problem by noting that many of the bodies in space appear similar to each other. By categorizing them suitably and then applying the scientific method to these groups of objects, we form a few theories that describe many objects and how they have evolved. These few theories can then be tested and refined as necessary. Such groupings of objects have proven invaluable, and they give us insights into the structure and organization of billions of stars and galaxies that are, indeed, very similar to one another.

Often several competing theories describe the same concepts with the same accuracy. In such cases, scientists choose the simplest one—namely, the theory that contains the fewest unproven assumptions. That basic tenet, formally expressed by the philosopher and Franciscan friar William of Occam in the fourteenth century, is known as **Occam's razor**. Indeed, the Sun-centered cosmology as refined by Johannes Kepler, which we are about to explore, was appealing because it made the same predictions within a simpler model than did the earlier Earth-centered cosmology. *Remember Occam's razor.*

#### Focus Question 2-1

Can you give an example of one scientific hypothesis and one nonscientific hypothesis not mentioned so far?

## Insight Into Science

**Science Is Inclusive** In principle, a scientific theory can be created, modified, or tested by anyone inclined to do so. In practice, however, being involved in the scientific enterprise requires that you understand the mathematical tools of science. Assuring that theories are written in terms of equations so that they can be carefully analyzed and tested by others is part of the process intended to prevent the scientific method from being derailed.

If the predictions of a theory are inconsistent with observations, the theory is modified, applied in more limited circumstances, or discarded in favor of a more accurate explanation. For example, Newton's law of gravitation is entirely adequate for describing the motion of an apple falling to Earth, the flight of a soccer ball, or the path of Earth orbiting the Sun; however, it is inaccurate in describing the orbit of Mercury around the Sun or the behavior of matter in the vicinity of very dense concentrations of matter, like black holes. In these cases, Newton's law of gravitation is replaced by Einstein's theory of general relativity, which describes gravitational behavior more accurately and over a much wider range of conditions than Newton's law but at the cost of much greater mathematical complexity. (The Global Positioning System, or GPS, requires such accurate measurements that scientists must include general relativity in the equations used to determine the locations of GPS satellites orbiting Earth.)

The scientific method can be summarized in six words: *observe, hypothesize, predict, test, modify,*

## Insight Into Science

**Theories and Beliefs** New theories are personal creations, but science is not a personal belief system. As stated in the previous Insight Into Science, scientific theories make predictions that can be tested by independent scientists. If everyone who performs tests of the theory's predictions gets results consistent with the theory, the theory is considered valid in that realm. In comparison, belief systems—such as which sports team or political system is best—are personal matters. People will always hold differing opinions about such issues.

*economize*. I urge you to watch for applications of the scientific method throughout this book. Our first encounter with it is the discovery that Earth orbits the Sun.

## CHANGING OUR EARTH-CENTERED VIEW OF THE UNIVERSE

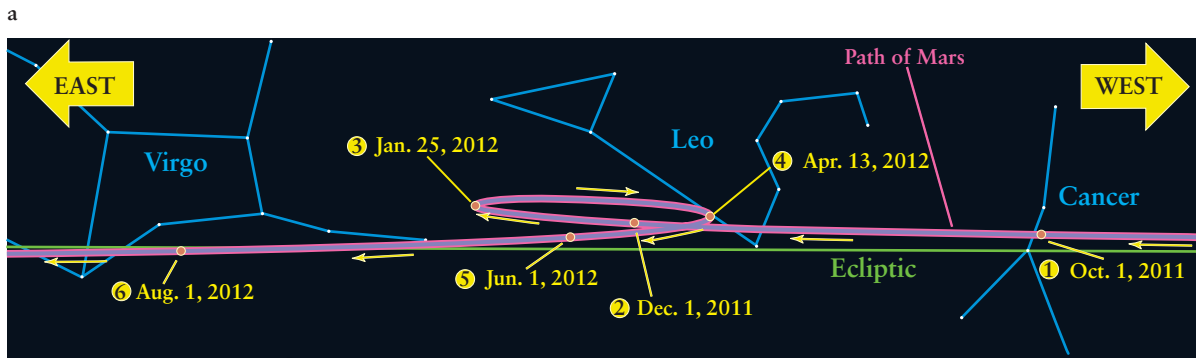
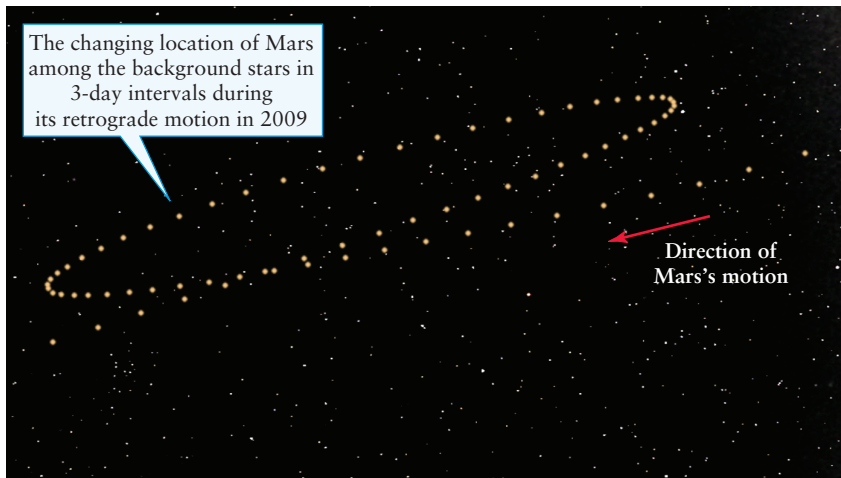
Early Greek astronomers tried to explain the motion of the five then-known planets: Mercury, Venus, Mars, Jupiter, and Saturn. Most people at that time held a *geocentric* view of the universe: Based on the observed motion of the celestial sphere, they believed that the Sun, the Moon, the stars, and the planets revolved around Earth. A theory of the overall structure and evolution of the universe is called a **cosmology**, so the prevailing Earth-centered cosmology was called *geocentric*. Geocentric cosmology, consistent as it is with casual observation of the sky, held sway until the sixteenth century, when Copernicus revolutionized our understanding of the cosmos.

### 2-2 The belief in a Sun-centered cosmology formed slowly

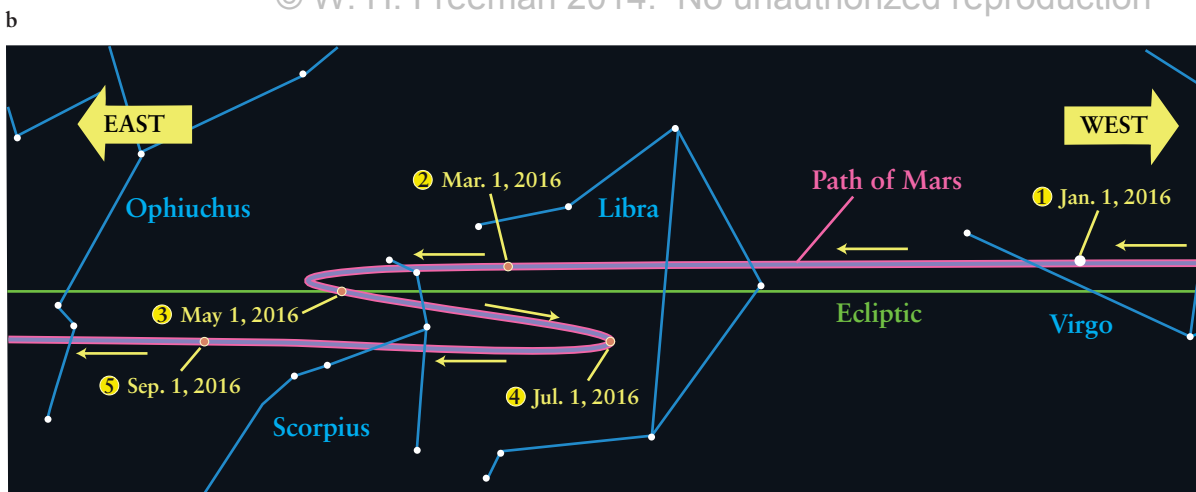
Explaining the motions of the five planets in a geocentric universe was one of the main challenges facing the astronomers of antiquity. The Greeks knew that the positions of the planets slowly shift relative to the “fixed” stars in the constellations. In fact, the word *planet* comes from a Greek term meaning “wanderer.” They also observed that planets do not move at uniform rates through the constellations. From night to night, as viewed in the northern hemisphere, the planets usually move slowly to the left (eastward) relative to the background stars. This movement is called **direct motion** or **prograde motion**. Occasionally, however, a planet seems to stop and then back up for several weeks or months. This reverse movement (to the right or westward relative to the background stars) is called **retrograde motion**. Both direct and retrograde motions are best observed by photographing (Figure 2-2a) or plotting (Figure 2-2b and 2-2c) the nightly position of a planet against the background stars over a long period.

All planetary motions on the celestial sphere are much slower than the apparent daily movement of the entire sky caused by Earth's rotation. Throughout a single night it is very difficult to detect motion of the planets among the stars. Therefore, the planets always rise with the stars in the eastern half of the sky and set with them in the western half.

The effort to understand planetary motion—and especially to explain retrograde motion—in a geocentric



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**Figure 2-2 Paths of Mars** (a) The retrograde motion of Mars as it would be seen in a series of images taken on the same photographic plate. (b) To help visualize this motion on the celestial sphere, astronomers often plot the position of Mars (or other body in retrograde motion) on a star chart. The

retrograde path is sometimes a loop north, as shown in (a) and (b), or south of the normal path, and sometimes an S-shaped path across the ecliptic. (c) In the middle of 2016, Mars will undergo an S-shaped retrograde motion.

cosmology resulted in an increasingly contrived and complex model (see **Discovery 2-1: Earth-Centered Universe**). The ancient Greek astronomer Aristarchus of Samos proposed a more straightforward explanation of planetary motion, namely, that all of the planets,

including Earth, revolve around the Sun. The retrograde motion of Mars in this **heliocentric** (Sun-centered) cosmology occurs because the faster-moving Earth overtakes and passes

#### Focus Question 2-2

Referring to Figure 2-2c, why do you think Mars is seen sometimes above the ecliptic and sometimes below it?

## DISCOVERY 2-1

### Earth-Centered Universe

Most of us find it hard to understand why anyone would believe that the Sun, planets, and stars orbit Earth. After all, we *know* that Earth spins on its axis. We *know* that the gravitational force from the Sun holds the planets in orbit, just as Earth's gravitational force holds the Moon in orbit. In childhood these facts become part of our understanding of the motions of the heavenly bodies.

Psychologists call this background information that we use to help explain things a *conceptual framework*. A conceptual framework contains all of the information we take for granted. For example, when the Sun rises, moves across the sky, and sets, we take for granted that it is Earth's rotation that causes the Sun's apparent motion.

Because they did not feel Earth move under their feet, or see any other indication that Earth is in motion, it did not even occur to our distant forebears to consider the possibility that we are in orbit around the Sun. The obvious conclusion for one who has a prescientific conceptual framework, even today, is that Earth stays put while objects in the heavens move around it. This prescientific conceptual framework for understanding the motions of the heavenly bodies was based on the senses and on common sense. That is, people observed motions and drew "obvious," commonsense conclusions. Today, we incorporate the known and tested laws of physics in our understanding of the natural world. Many of these realities are utterly counterintuitive and, therefore, the conceptual frameworks that we possess are less consistent with common sense

than those held in the past. Studying science helps us to develop intuition that is consistent with the actual workings of nature.

**Geocentric Explanation of the Planets' Retrograde Motion** The early Greeks, working in what we now know is an incorrect geocentric (Earth-centered) cosmology, developed many theories to account for the occasional retrograde motion of the planets and the resulting loops that the planets trace out against the background stars. One of the most successful (albeit incorrect) ideas was expounded by the last of the great ancient Greek astronomers, Ptolemy, who lived in Alexandria, Egypt. His basic concepts are sketched in **Figure D2-1**. Each planet is assumed to move in a small circle called an *epicycle*, the center of which moves in a larger circle called a *deferent*, whose center is offset from Earth. As viewed from Earth, the epicycle moves eastward along the deferent, and both the epicycle and the planet on it revolve in the same direction (counterclockwise in the figure).

Most of the time, the motion of the planet on its epicycle adds to the eastward motion of the epicycle on the deferent. Thus, the planet is seen from Earth to be in direct motion (to the left or eastward) against the background stars throughout most of the year (Figure D2-1a). However, when the planet is on the part of its epicycle nearest Earth, its motion along the epicycle subtracts from the motion of the epicycle along the deferent. The planet thus appears to slow and then halt its usual movement to the left (eastward motion) among the constellations and then

the Red Planet (**Figure 2-3**). The occasional retrograde movement of a planet is merely the result of our changing viewpoint as we orbit the Sun—an idea that is beautifully simple compared to the geocentric system with all of its complex planetary motions. (The word *heliocentric* is misleading. Although the local planets, moons, and small pieces of space debris do orbit the Sun, the stars and innumerable other objects in space do not. In fact, the Sun and the bodies that orbit it all orbit the center of our Milky Way Galaxy.)

### 2-3 Copernicus devised the first comprehensive heliocentric cosmology

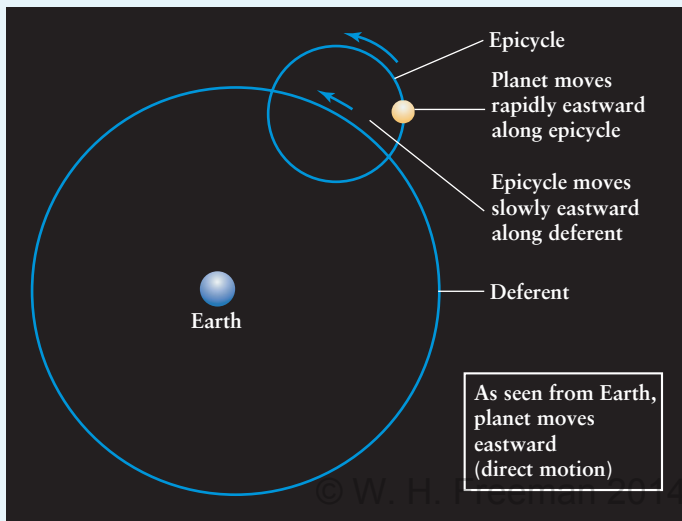
Over the centuries following Aristarchus, increasingly accurate observations of the planets' locations revealed errors in the predictions of geocentric cosmology. To reconcile that cosmology with the data, more and more

complex motions were attributed to the planets. By the mid-1500s, the geocentric cosmology had become truly unwieldy in its efforts to predict the motions of the planets accurately. It was then that the Polish mathematician, lawyer, physician, economist, cleric, and artist Nicolaus Copernicus resurrected Aristarchus's theory. Copernicus was motivated by an effort to simplify the celestial scheme, and eventually his heliocentric cosmology did just that.

Pursuing the heliocentric cosmology, Copernicus determined, by observations, which planets are closer to the Sun than Earth and which are farther away. Because Mercury and Venus are always observed fairly near the Sun, he correctly concluded that their orbits must lie inside Earth's orbit. The other planets visible to Copernicus—Mars, Jupiter, and Saturn—can sometimes be seen high in the sky in the middle of the night, when the Sun is far below the horizon. This placement can occur only

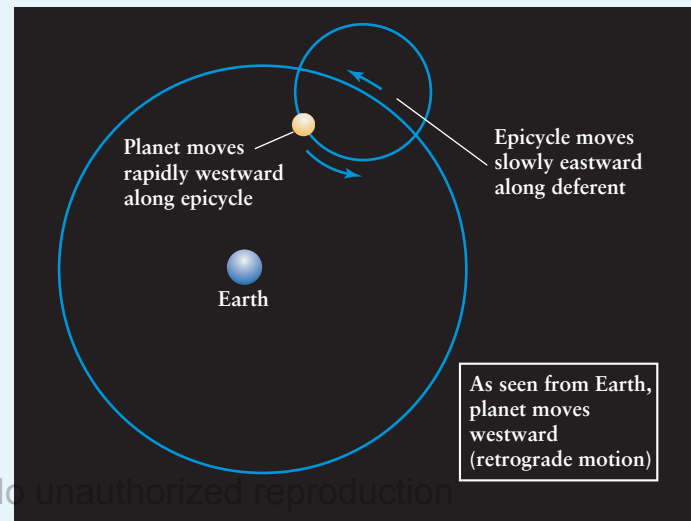
seems to move to the right (westward) among the stars for a few weeks or months (Figure D2-1b). This concept of epicycles and deferents enabled Greek astronomers to explain the retrograde loops of the planets. Ptolemy's

geocentric cosmology endured as a useful predictor of the motions of the Sun, Moon, and planets for more than 1000 years.



a

**FIGURE D2-1 A Geocentric Explanation of Planetary Motion** Each planet revolves around an epicycle, which in turn revolves around a deferent centered approximately on Earth. As seen from Earth, the speed of the planet on the epicycle



b

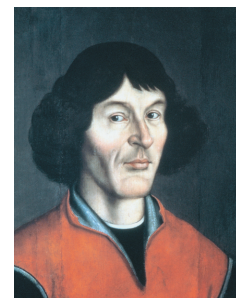
alternately (a) adds to or (b) subtracts from the speed of the epicycle on the deferent, thus producing alternating periods of direct and retrograde motions.

if Earth comes between the Sun and a planet. Copernicus therefore concluded (also correctly) that the orbits of Mars, Jupiter, and Saturn lie outside Earth's orbit. Today, Mercury and Venus are called **inferior planets**, while all the planets farther from the Sun than Earth are called **superior planets**.

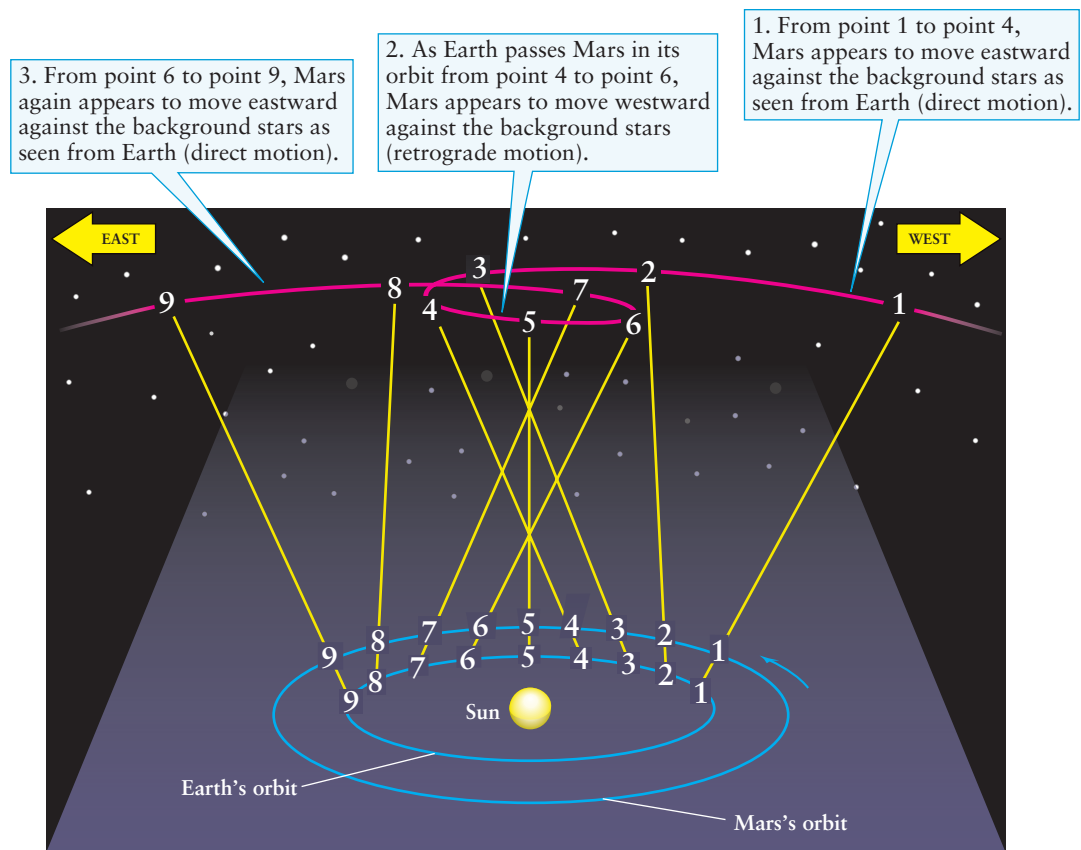
The geometric arrangements among Earth, another planet, and the Sun are called **configurations**. For example, when Mercury or Venus is directly between Earth and the Sun (Figure 2-4), we say the planet is in a configuration called an **inferior conjunction**; when either of these planets is on the opposite side of the Sun from Earth, its configuration is called a **superior conjunction**.

The angle between the Sun and a planet as viewed from Earth is called the planet's **elongation**. A planet's elongation varies from zero degrees to a maximum value, depending upon where we see it in its orbit around the Sun. At *greatest eastern* or *greatest western elongation*,

Mercury and Venus are as far from the Sun in angle as they can be. This position is about  $28^\circ$  for Mercury and about  $47^\circ$  for Venus. The superior planets all have maximum elongations of  $180^\circ$ . When either Mercury or Venus rises before the Sun, the planet is visible in the eastern sky as a bright “star” and is often called the “morning star.” Similarly, when either of these two planets sets after the Sun, the planet is visible in the western sky and is then called the “evening star.” Because these two planets are not always at their greatest elongations, they are often very close in angle to the Sun. This positioning is especially true of Mercury, often making it

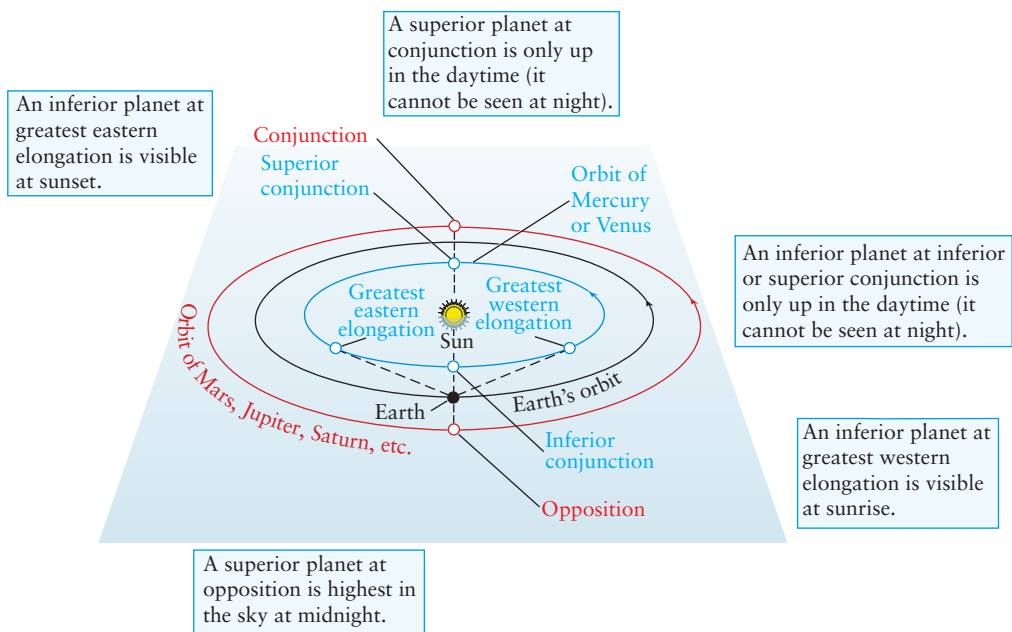


Nicolaus Copernicus  
(1473–1543)  
(Universal History  
Archive/Getty Images)



**FIGURE 2-3 A Heliocentric Explanation of Retrograde Motion** Earth travels around the Sun more rapidly than does Mars. Consequently, as Earth overtakes and passes this slower-

moving planet, Mars appears (from points 4 through 6) to move backward among the background stars for a few months.



**FIGURE 2-4 Planetary Configurations** Key points along a planet's orbit have names, as shown. These points identify spe-

cific geometric arrangements between Earth, another planet, and the Sun.

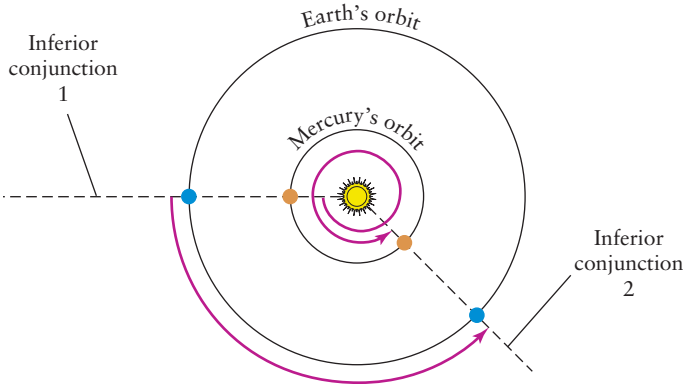
hard to see from Earth. Venus is often nearly halfway up the sky at sunrise or sunset and therefore quite noticeable during much of its orbit. Because they are so bright and sometimes appear to change color due to the motion of Earth's atmosphere, Venus and Mercury are often mistaken for UFOs. (The same motion of the air causes the road in front of your car to shimmer on a hot day.)

Planets farther from the Sun than Earth have different configurations. When one of these planets is located behind the Sun, as seen from Earth, that planet is said to be in **conjunction**. When a planet is opposite the Sun in the sky, that planet is at **opposition**. It is not difficult to determine when a planet happens to be located at one of the key positions in Figure 2-4. For example, when Mars is at opposition, it appears high and bright in the sky at midnight.

It is relatively easy to follow a planet as it moves from one configuration to another. However, these observations alone do not tell us the planet's actual orbit, because Earth, from which we make the observations, is also moving. Copernicus was therefore careful to distinguish between two characteristic time intervals, or *periods*, of each planet.

Recall from Chapter 1 that a planet's **sidereal period** is the time it takes that body to make one complete orbit of the Sun as measured with respect to the distant stars; an observer fixed at the Sun's location watching that planet would see it start at one point on the celestial sphere, go around the sphere, and end at the same place it started from. *The sidereal period or orbit is the length of a year for each planet.*

The other useful time interval that Copernicus used is the **synodic period**. The synodic period is the time that elapses between two successive identical configurations as seen from Earth. This period can be from one opposition to the next, for example, or from one conjunction to



**FIGURE 2-5 Synodic Period** The time between consecutive conjunctions of Earth and Mercury is 116 days. As is typical of synodic periods for all planets, the location of Earth is different at the beginning and end of the period. You can visualize the synodic periods of the outer planets by putting Earth in Mercury's place in this figure and putting one of the outer planets in Earth's place.

**TABLE 2-1** **SYNODIC AND SIDEREAL PERIODS OF THE PLANETS (IN EARTH YEARS)**

	Synodic (year)	Sidereal (year)
Mercury	0.318	0.241
Venus	1.599	0.616
Earth	—	1.0
Mars	2.136	1.9
Jupiter	1.092	11.9
Saturn	1.035	29.5
Uranus	1.013	84.0
Neptune	1.008	164.8

the next (of the same type, **Figure 2-5**). The synodic period tells us, among other things, when to expect a planet to be closest to Earth and, therefore, most easily studied.

**Focus Question 2-3**  
Why do I say “of the same type” in this paragraph?

Thus, nearly 500 years ago, Copernicus was able to obtain the first six entries shown in **Table 2-1** (the others are contemporary results included for completeness). Copernicus was then able to devise a straightforward geometric method for determining the distances of the planets from the Sun. His answers turned out to be remarkably close to the modern values, as shown in **Table 2-2**. From these two tables it is apparent that the farther a planet is from the Sun, the longer it takes to complete its orbit.

Copernicus presented his heliocentric cosmology, including supporting observations and calculations, in a book entitled *De revolutionibus orbium coelestium* (*On the Revolutions of the Celestial Spheres*), which was published in 1543, the year of his death. His great

**TABLE 2-2** **AVERAGE DISTANCES OF THE PLANETS FROM THE SUN**

	Measurement (AU)	
	By Copernicus	Modern
Mercury	0.38	0.39
Venus	0.72	0.72
Earth	1.00	1.00
Mars	1.52	1.52
Jupiter	5.22	5.20
Saturn	9.07	9.54
Uranus	Unknown	19.19
Neptune	Unknown	30.06

insight was the conceptual simplicity of a heliocentric cosmology compared to geocentric views, especially in explaining retrograde motion. However, Copernicus incorrectly assumed that the planets travel along circular paths around the Sun. Without using epicycles similar to those used in geocentric theory (see Figure D2-1), many of his predictions were no more accurate than those of the earlier theory, as we will see shortly.

## 2-4 Tycho Brahe made astronomical observations that disproved ancient ideas about the heavens

In November 1572, a bright star suddenly appeared in the constellation Cassiopeia. At first, it was even brighter than Venus, but then it began to grow dim. After 18 months the star faded from view.

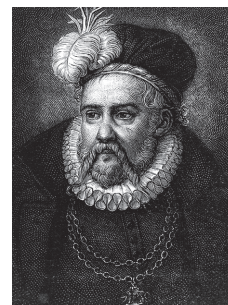
Modern astronomers recognize this event as a supernova explosion, the violent death of a certain type of star (see Chapter 11). In the sixteenth century, however, the prevailing opinion was quite different. Teachings dating back to Aristotle and Plato argued that the heavens were permanent and unalterable. From that perspective, the “new star” of 1572 could not really be a star at all, because the heavens do not change. Many astronomers and theologians of the day argued that the sighting must be some sort of bright object quite near Earth, perhaps not much farther away than the clouds overhead. A 25-year-old Danish astronomer named Tycho Brahe realized that straightforward observations might reveal the distance to this object.

Consider what happens when two people look at a nearby object from different places—they see it in different positions relative to the things behind it. Furthermore, their heads face at different angles when looking at it. This variation in angle that occurs when viewing a nearby object from different locations is called **parallax** (Figure 2-6).

Tycho reasoned as follows: If the new star is nearby, its position should shift against the background stars over the course of a night (Figure 2-7a). His

careful observations, done in the spirit of the scientific method, failed to reveal any parallax, and so the new star had to be far away, farther from Earth than anyone had imagined (Figure 2-7b). Tycho summarized his findings in a small book, *De nova stella* (*On the New Star*), published in 1573.

From 1576 to 1597, Tycho made comprehensive observations, measuring planetary positions with an accuracy of 1 arcminute (arcmin; see Section 1-5), about as precise as is possible with nontelescopic instruments (the telescope was invented in 1608). Upon Tycho’s death in 1601, most of his invaluable astronomical records were given to his gifted assistant, Johannes Kepler.



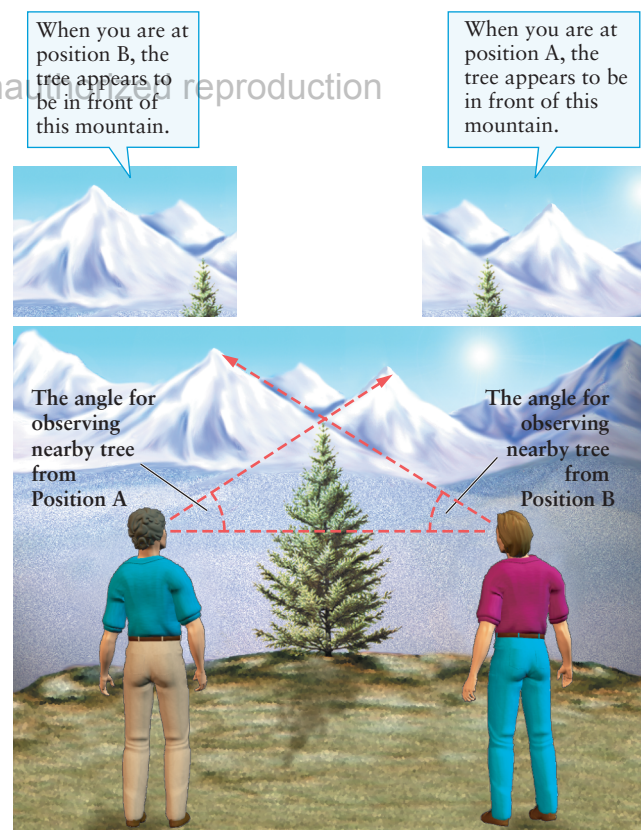
Tycho Brahe (1546–1601), also depicted within the portrait of Kepler (INTERFOTO/Alamy)

### Focus Question 2-4

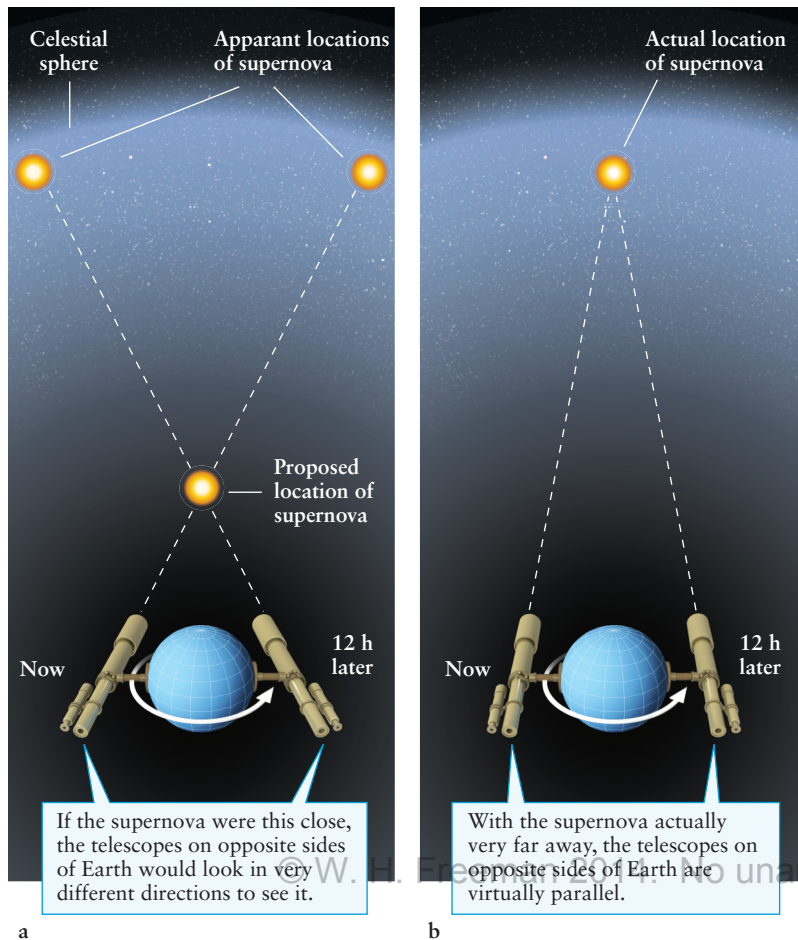
Describe a simple experiment to demonstrate that your eyes (and, implicitly, your brain) use parallax to determine distances.

### Insight Into Science

**Take a Fresh Look** When a scientific concept is hard to visualize, try another perspective. For example, a planet’s sidereal period of orbit is easy to understand when viewed from the Sun but more complicated as seen from Earth. The synodic period of each planet, on the other hand, is easily determined from Earth. As we will see, especially when we study Einstein’s theories of relativity, each of these perspectives is called a *frame of reference*.



**FIGURE 2-6 Parallax** Nearby objects are viewed at different angles from different places, an effect called parallax. These objects also appear to be in different places with respect to more distant objects when viewed by observers located at different positions. Parallax is used by astronomers, surveyors, and sailors to determine distances.



**FIGURE 2-7 The Parallax of a Nearby Object in Space** Tycho thought that Earth does not rotate and that the stars revolve around it. From our modern perspective, the changing position of the supernova would be due to Earth's rotation as shown. **(a)** Tycho argued that if an object is near Earth, its position relative to the background stars should change over the course of a night. **(b)** Tycho failed to measure such changes for the supernova in 1572. This is illustrated in (b) by the two telescopes being parallel to each other. He, therefore, concluded that the object was far from Earth.

## KEPLER'S AND NEWTON'S LAWS

Until Kepler's time, astronomers had assumed that heavenly objects move in circles. For philosophical and aesthetic reasons, circles were considered the most perfect and most harmonious of all geometric shapes. However, using circular orbits failed to yield accurate predictions for the positions of the planets. For years, Kepler tried to find a shape for orbits that would fit Tycho's observations of the planets' positions against the background of distant stars. Finally, he began working with a geometric form called an **ellipse**.

### 2-5 Kepler's laws describe orbital shapes, changing speeds, and the lengths of planetary years

You can draw an ellipse as shown in **Figure 2-8a**. Each thumbtack is at a **focus** (plural **foci**). The longest diameter (major axis) across an ellipse passes through both foci. Half of that distance is called the **semimajor axis**. In astronomy, the length of the semimajor axis is also the average distance between a planet and the Sun.

**2** To Kepler's delight, the ellipse turned out to be the curve for which he had been searching. Predictions of the locations of planets based on elliptical paths were

in very close agreement with where the planets actually were. Keep in mind that the following three laws that Kepler discovered merely quantified (gave equations for) observations that Tycho had made—Kepler did not have a theory to explain them. That would come nearly 80 years later with the work of Isaac Newton.

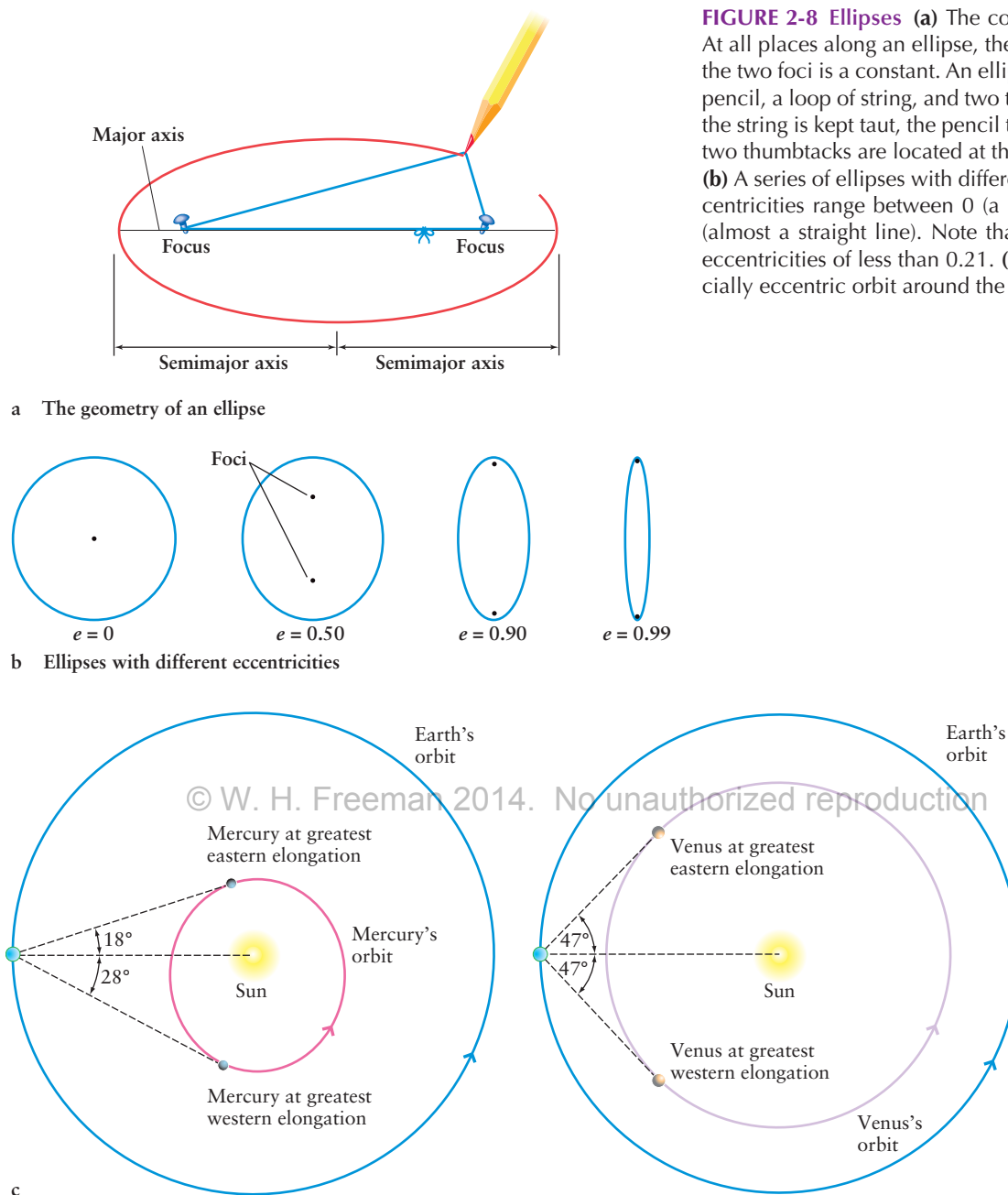
Kepler published his discovery of elliptical orbits in 1609 in a book known today as *New Astronomy*. This important discovery is now considered the first of **Kepler's laws**:

**Kepler's First Law:** *The orbit of each planet around the Sun is an ellipse with the Sun at one focus.*

The shapes of ellipses have two extremes. The roundest ellipse, occurring when the two foci merge, is a circle. The most elongated ellipse is nearly a straight line. The shape of a planet's orbit around the Sun is described by its **orbital eccentricity**, designated by the letter  $e$ , which ranges from 0 (a circular orbit) to just under 1.0 (nearly



Johannes Kepler  
(1571–1630) (Science Source)

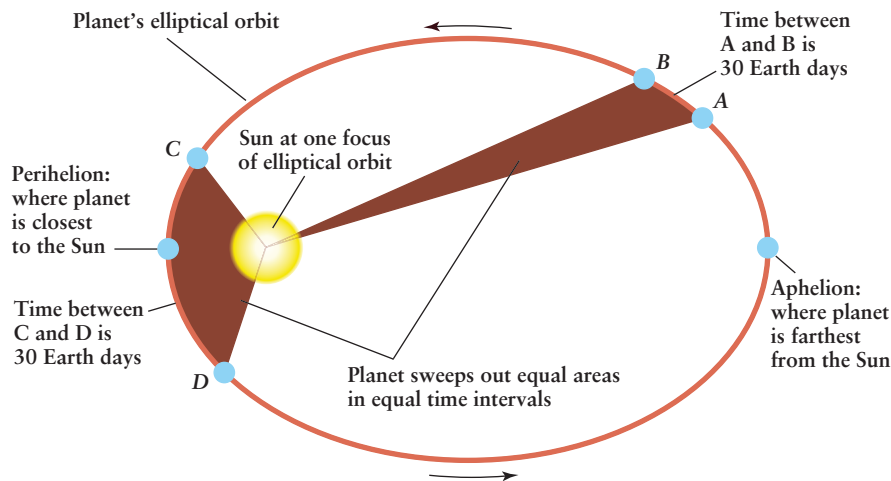


a straight line). Figure 2-8b shows a sequence of ellipses and their associated eccentricities. Observations have revealed that there is no object at the second focus of each elliptical planetary orbit. Figure 2-8c shows the effect of orbital eccentricity. For example, the maximum elongation of Mercury ( $e = 0.21$ ) seen from Earth varies by  $10^\circ$ , while the maximum elongation of Venus ( $e = 0.01$ ) varies by less than  $1^\circ$ .

**3** Tycho's observations also showed Kepler that planets do not move at uniform speeds along their orbits. Rather, a planet moves fastest when it is nearest the Sun, a point on its orbit called **perihelion**. Conversely,

a planet moves most slowly when it is farthest from the Sun, a point called its **aphelion**.

After much trial and error, Kepler discovered a way to describe how fast a planet moves anywhere along its orbit. This discovery, also published in *New Astronomy*, is illustrated in Figure 2-9. Suppose that it takes 30 days for a planet to go from point A to point B. During that time, the line joining the Sun and the planet sweeps out a nearly triangular area (shaded in Figure 2-9). Kepler discovered that the line joining the Sun and the planet sweeps out the same area during any other 30-day interval. In other words, if the planet



**FIGURE 2-9 Kepler's First and Second Laws** According to Kepler's first law, every planet travels around the Sun along an elliptical orbit with the Sun at one focus. According to his second law, the line joining the planet and the Sun sweeps out equal areas (the burgundy-colored regions) in equal intervals of time (time from A to B equals time from C to D). *Note:* This drawing shows a highly elliptical orbit, with  $e = 0.74$ . Even though this is a much greater eccentricity than that of any planet in the solar system, the concept still applies to all planets and other orbiting bodies.

also takes 30 days to go from point C to point D, then the two shaded segments in Figure 2-9 are equal in area. Kepler's second law, also called the **law of equal areas**, can be stated thus:

**Kepler's Second Law:** *A line joining a planet and the Sun sweeps out equal areas in equal intervals of time.*

A consequence of Kepler's second law is that each planet's speed decreases as it moves from perihelion to aphelion. The speed then increases as the planet moves from aphelion toward perihelion.

Kepler was also able to relate a planet's year to its distance from the Sun. This discovery, published in 1619, is Kepler's third law. This relationship predicts the planet's sidereal period if we know the length of the semimajor axis of the planet's orbit:

**Kepler's Third Law:** *The square of a planet's sidereal period around the Sun is directly proportional to the cube of the length of its orbit's semimajor axis.*

The relationship is easiest to use if we let  $P$  represent the sidereal period of an object's orbit around the Sun in Earth years and  $a$  represent the length of its semimajor

axis (that is, its average distance from the Sun) measured in **astronomical units (AU)**. One astronomical unit is the average distance from Earth to the Sun; hence,  $a = 1$  for Earth. The astronomical unit is used when measuring distances between objects in the solar system, because no powers of ten are needed, as they would be if these distances were referred to in kilometers or miles. (See **Discovery 2-2: Units of Astronomical Distance** for more details.) Now we can write Kepler's third law for all objects orbiting the Sun as

$$P^2 = a^3$$

4 This equation says that a planet closer to the Sun has a shorter year than does a planet farther from the Sun. Using this equation with Kepler's second law reveals that planets closer to the Sun move more rapidly than those farther away. Using data from Table 2-1 and Table 2-2, we can demonstrate Kepler's third law as shown in **Table 2-3**.

**Focus Question 2-5**  
What is the shape of the International Space Station's orbit around Earth?

**Focus Question 2-6**  
We saw in Chapter 1 that the Moon's orbit around Earth is not circular. Where in its orbit is the Moon moving fastest, and where is it moving slowest?

**TABLE 2-3 A DEMONSTRATION OF KEPLER'S THIRD LAW**

	Sidereal period $P$ (year)	Semimajor axis $a$ (AU)	$P^2$	=	$a^3$
Mercury	0.24	0.39	0.06		0.06
Venus	0.61	0.72	0.37		0.37
Earth	1.00	1.00	1.00		1.00
Mars	1.88	1.52	3.53		3.51
Jupiter	11.86	5.20	140.7		140.6
Saturn	29.46	9.54	867.9		868.3
Uranus	84.01	19.19	7058		7067
Neptune	164.79	30.06	27,160		27,160

## DISCOVERY 2-2

### UNITS OF ASTRONOMICAL DISTANCE

Throughout this book we will find that some of our traditional units of measure become cumbersome. It is fine to use kilometers to measure the diameters of craters on the Moon or the heights of volcanoes on Mars. However, it is as awkward to use kilometers to express the large distances to planets, stars, or galaxies as it is to talk about the distance from New York City to San Francisco or Sydney to Perth in millimeters. Astronomers have therefore devised new units of measure.

When discussing distances across the solar system, astronomers use a unit of length called the astronomical unit (AU), which is the average distance between Earth and the Sun:

$$1 \text{ AU} \approx 1.5 \times 10^8 \text{ km} \approx 9.3 \times 10^7 \text{ mi}$$

Jupiter, for example, is an average of 5.2 times farther from the Sun than is Earth. Thus, the average distance between the Sun and Jupiter can be conveniently stated as 5.2 AU. This value can be converted into kilometers or miles using the previous relationship.

When talking about distances to the stars, astronomers choose between two different units of length. One is the **light-year (ly)**. A light-year is the *distance* that light travels in a year through a vacuum (that is, in the absence of air, glass, or other medium). Do keep in mind that the word *year* in this unit helps describe a separation between two objects rather than representing a unit of time.

$$1 \text{ ly} \approx 9.46 \times 10^{12} \text{ km} \approx 63,200 \text{ AU}$$

The spaces between the planets, stars, and galaxies are nearly ideal vacuums. One light-year is roughly equal to 6 trillion miles. Proxima Centauri, the closest star to Earth, other than the Sun, is just over 4.2 ly from us.

The second commonly used unit of length is the **parsec (pc)**, the distance at which two objects separated by 1 AU make an angle of 1 arcsec (denoted  $1''$ ). Imagine taking a journey far into space, beyond the orbits of the outer planets. Watching the solar system as you move away, the angle between the Sun and Earth becomes smaller and smaller. When they are side by side from your perspective, and you measure the angle between them as  $1/3600^\circ = 1''$ , you have reached a distance that astronomers call 1 parsec, as shown in the accompanying figure. The parsec turns out to be longer than the light-year, specifically,

$$1 \text{ pc} \approx 3.09 \times 10^{13} \text{ km} \approx 3.26 \text{ ly}$$

Thus, the distance to the nearest star can be stated as 1.3 pc as well as 4.2 ly. Whether one uses light-years or parsecs is a matter of personal preference.

For larger distances, *kilolight years (kly)*, *megalight years (Mly)*, *kiloparsecs (kpc)*, and *megaparsecs (Mpc)* are used. The prefixes *kilo* and *mega* simply mean “thousand” and “million,” respectively:

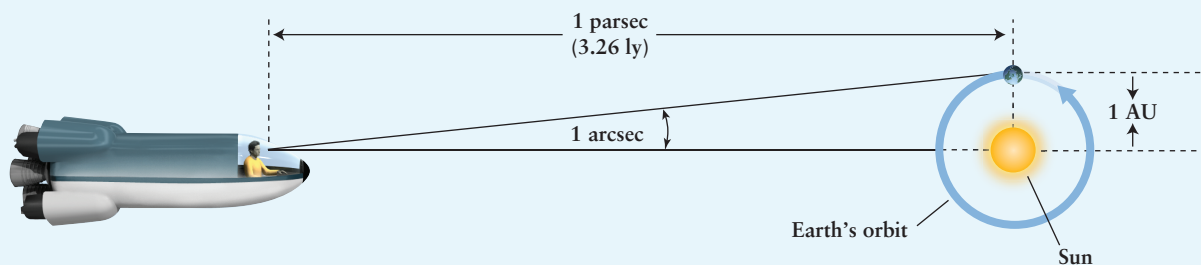
$$1 \text{ kly} = 10^3 \text{ ly}$$

$$1 \text{ Mly} = 10^6 \text{ ly}$$

$$1 \text{ kpc} = 10^3 \text{ pc}$$

$$1 \text{ Mpc} = 10^6 \text{ pc}$$

For example, the distance from Earth to the center of our Milky Way Galaxy is about 8.6 kpc, and the rich cluster of galaxies in the direction of the constellation Virgo is 20 Mpc away.



**FIGURE D2-2 A Parsec** The parsec, a unit of length commonly used by astronomers, is equal to 3.26 ly. The parsec

is defined as the distance at which 1 AU perpendicular to the observer's line of sight makes an angle of 1 arcsec.

When Newton derived Kepler's third law using the law of gravitation, discussed later in this chapter, he discovered that the mass of a planet affects the period of its orbit around the Sun. The **mass** of an object is a measure of the total number of particles of all different types that

it contains and is expressed in units of kilograms. For example, the mass of the Sun is  $2 \times 10^{30} \text{ kg}$ , the mass of a hydrogen atom is  $1.7 \times 10^{-27} \text{ kg}$ , and the mass of the author of this book is 83 kg. At rest, the Sun, a hydrogen atom, and I have these same masses regardless of where

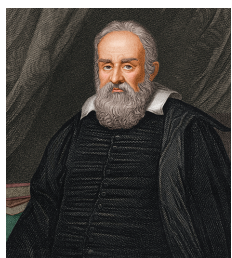
we happen to be in the universe. It is important not to confuse the concept of mass with the concept of weight. Your **weight** is the force with which you push down on a scale due to the gravitational attraction of the world on which you stand.

However, the effect of the planet's mass on the period of its orbit is exceedingly small for all the planets in the solar system, which is why the equation for Kepler's third law, as shown in Table 2-3, gives such good results for the planets' orbits even though it does not take their masses into account. When calculating the motion of pairs of stars orbiting each other, the effects of the masses must be included, as described in **Discovery 9-3: Kepler's Third Law and Stellar Masses**.

Kepler's three laws apply not only to the planets orbiting the Sun but also to any object orbiting another under the influence of their mutual gravitational attraction. Thus, Kepler's laws apply to moons orbiting planets, artificial satellites orbiting Earth, and even (with the above caveat) two stars revolving around each other.

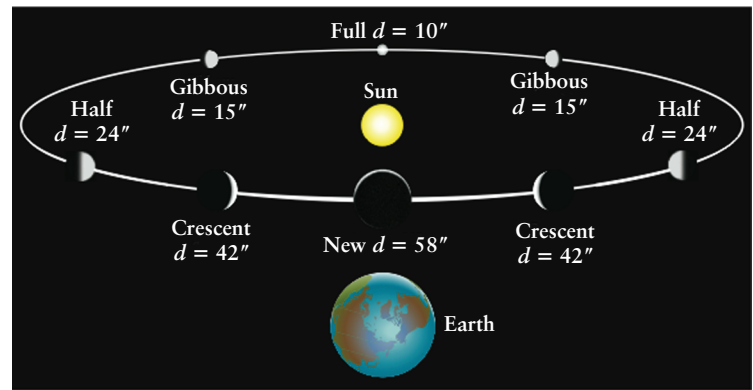
## 2-6 Galileo's discoveries strongly supported a heliocentric cosmology

While Kepler was in central Europe working on the laws of planetary orbits, an Italian physicist was making dramatic observations in southern Europe. Galileo Galilei did not invent the telescope, but he was one of the first people to point the new device toward the sky and publish his observations. He saw things that no one had ever imagined—mountains on the Moon and spots on the Sun. He also discovered that like our Moon, Venus has phases from new to full and that the change in the apparent size of Venus as seen through his telescope was related to the planet's phase (**Figure 2-10**). Venus appears smallest at full phase and largest at new phase. These observations were a big chink in the geocentric cosmology's armor, as that model could not explain why Venus has a complete cycle of phases or changes size, while a heliocentric cosmology explains both. (Since Venus is always near the Sun in our sky, the geocentric model predicts that Venus should always have a crescent or quarter phase if it is closer to us than the Sun or a full or gibbous phase if it is farther away than the Sun—see **Figure 2-10**.) Galileo's observations of a complete cycle of phases, therefore, supported the conclusion that Venus orbits the Sun, not Earth.



Galileo Galilei  
(1564–1642) (Stock  
Montage, Inc./Alamy)

In 1610, Galileo also discovered four moons near Jupiter. Today, in honor of their discoverer, these are called the **Galilean moons** (or **satellites**, another term for moons). Galileo concluded that the moons



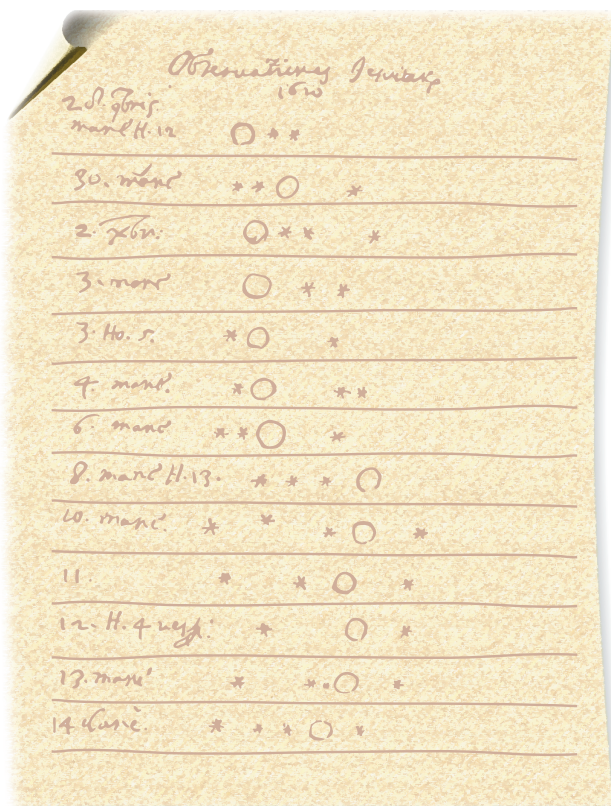
**FIGURE 2-10 The Changing Appearance of Venus** This figure shows how the appearance (phase) of Venus changes as it moves along its orbit. The number below each view is the angular diameter ( $d$ ) of the planet as seen from Earth, in arcseconds. The " indicates arcseconds, as introduced in Section 1-5 and again in **Discovery 2-2: Units of Astronomical Distance**. Note that the phases correlate with the planet's angular size and its angular distance from the Sun, both as seen from Earth. These observations clearly support the idea that Venus orbits the Sun.

orbit Jupiter because he saw them move in straight lines from one side of the planet to the other. (He did not see them move in elliptical orbits because from Earth we see their orbits from edge-on.) Confirming observations were made in 1620 (**Figure 2-11**). These observations all provided further evidence that Earth is not at the center of the universe. Like Earth in orbit around the Sun, Jupiter's four moons obey Kepler's third law: The square of a moon's orbital period around Jupiter is directly proportional to the cube of its average distance from the planet.

Galileo's telescopic observations constituted the first fundamentally new astronomical data since humans began recording what they saw in the sky. In contradiction to then-prevailing opinions, these discoveries strongly supported a heliocentric view of the universe. Because Galileo's ideas could not be reconciled with certain passages in the Bible or with the writings of Aristotle and Plato, the Roman Catholic Church condemned him, and he was forced to spend his later years under house arrest "for vehement suspicion of heresy."

### Insight Into Science

**Theories and Explanations** Scientific theories (or laws) based on observations can be useful for making predictions even if the reasons that these theories work are unknown. The explanation for Kepler's laws came decades after Kepler deduced them, when Newton derived them in 1665 with his mathematical expression for gravitation, the force that holds the planets in their orbits.



a

**FIGURE 2-11 Jupiter and Its Largest Moons** In 1610, Galileo discovered four “stars” that move back and forth across Jupiter. He concluded that they are four moons that orbit Jupiter just as our Moon orbits Earth. **(a)** Observations made by Jesuits in 1620 of Jupiter and its four visible moons. **(b)** Photograph of the four Galilean satellites alongside an overexposed image of Jupiter. Each satellite would be bright enough to be seen with the unaided eye were it not overwhelmed by the glare of Jupiter. (Rev. Ronald Royer/Science Source)



b

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In 1992, Pope John Paul II stated that the Church erred in this condemnation.

A major stumbling block prevented seventeenth-century thinkers from accepting Kepler’s laws and Galileo’s conclusions about the heliocentric cosmology. Once anything on Earth is put in motion, it quickly comes to rest. So why don’t the planets orbiting the Sun stop, too?

The scientific method clarified most of the issues surrounding planetary orbits, leading to the equations and laws developed by the brilliant and eccentric scientist Isaac Newton (for example, he believed in alchemy). He was born on Christmas Day in 1642, less than a year after Galileo died. In the decades that followed, Newton revolutionized science more profoundly than any person before him and, in doing so, he found physical and mathematical evidence in support of the heliocentric cosmology.

## 2-7 Newton formulated three laws that describe fundamental properties of physical reality

Until the mid-seventeenth century, virtually all mathematical astronomy was done empirically. That is, astronomers from Ptolemy to Kepler created equations directly from data and observations.

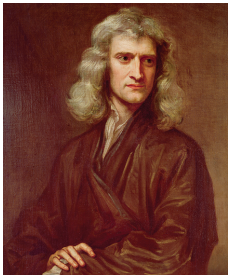
Isaac Newton introduced a new approach. He began with three physical assumptions, now called **Newton’s laws of motion**, which led to equations that have since been tested and shown to be correct in many everyday

situations. He also found a formula for the force of **gravity** (or *gravitation*), the attraction between all objects due to their masses. Putting the assumptions into mathematical form and combining them with the equation for gravity, Newton was able to derive Kepler’s three laws and use them to predict the orbits of bodies such as comets and other objects in the solar system. Newton also was able to use these same equations to predict the motions of bodies on and near Earth, such as the path of a projectile or the speed of a falling object.

**Newton’s First Law—The Law of Inertia:** *Inertia is the property of matter that keeps an object at rest or moving in a straight line at a constant speed unless acted upon by a net external force.*

If all of the external forces acting on an object do not cancel each other out, then there is a net external force acting on the object. Equivalently, we say that there is an unbalanced external force. For example, if you put a soccer ball between your hands and press on it so that it does not move, your hands represent a balanced pair of forces acting on the ball. In that case, you are exerting no net external force on the ball. Conversely, when your foot hits a soccer ball and the ball sails away, your foot has exerted a net external force on the ball.

At first, this law might seem to conflict with your everyday experience. For example, if you shove a chair, it does not move at a constant speed forever but comes to rest after sliding only a short distance. From Newton’s



Isaac Newton (1642–1727) (Lebrecht Music and Arts Photo Library/Alamy)

viewpoint, however, a “net external force” does indeed act on the moving chair—namely, friction between the chair’s legs and the floor. Without friction, the chair would continue in a straight path at a constant speed. A net external force changes the motion of an object.

Newton’s first law tells us why the planets keep moving in orbit around the Sun. First, they do not come to rest because there is virtually no air in space and hence

no force from, for example, air friction opposing their motion. Second, they do not move in straight lines because there is an outside force acting on the planets to continually change their directions and keep them in orbit. As we shall see, that force is the Sun’s gravity.

Newton’s second law describes quantitatively how a force changes the motion of an object. To better appreciate the concepts of force and motion, we must first understand two related quantities: velocity and acceleration.

Imagine an object motionless in space. Push on it and it begins to move. At any moment, you can describe the object’s motion by specifying both its speed and direction. Speed and direction of motion together constitute an object’s **velocity**. If you continue to push on the object, its speed will increase—it will accelerate.

**Acceleration** is the rate at which velocity changes with time. Because velocity involves both speed and direction, a slowing down, a speeding up, and a change in direction are all forms of acceleration.

Suppose, for example, an object revolved around the Sun in a perfectly circular orbit. As this object moved along its orbit, its speed would remain constant, but its direction of motion would be continuously changing. This body would have acceleration that involved only a change of direction. In general:

**Newton’s Second Law—The Force Law:** *The acceleration of an object is directly proportional to the net force acting on it and is inversely proportional to its mass.*

In other words, the harder you push on something that can move, the faster it will accelerate. Also, an object of greater mass accelerates more slowly when acted on by a force than does an object of lesser mass acted on by the same force. That is why you can accelerate a child’s wagon faster than you can accelerate a car by pushing on them equally hard.

Newton’s second law can be succinctly stated as an equation. If a **force** acts on an object, the object will experience an acceleration such that

$$\text{Force} = \text{mass} \times \text{acceleration}$$

**5** Force is usually expressed in pounds or newtons. For example, the force with which I am pressing down on the ground is 814 newtons (183 lb). But I weigh 814 newtons only on Earth. I would weigh 136 newtons (30.5 lb) on the Moon, which has less mass and so pulls me down with less gravitational force. Orbiting in the International Space Station, my weight (measured by standing on a scale in the space station) would be 0, but my mass would be the same as when I am on Earth. Whenever we describe the properties of planets, stars, or galaxies, we speak of their masses, never of their weights.

Newton’s final assumption, called *Newton’s third law*, is the law of action and reaction.

**Newton’s Third Law—The Law of Action and Reaction:** *Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first object.*

For example, I weigh 183 lb on Earth, and so I press down on the floor with a force of 183 lb. Newton’s third law says that the floor is also pushing up against me with an equal force of 183 lb. (If it were less, I would fall through the floor, and if it were more, I would be lifted upward.) Even two objects that are not touching exert equal and opposite gravitational forces on each other. The Sun is exerting a force on each planet to keep it in orbit; hence, each planet exerts an equal and opposite force on the Sun. As each planet accelerates toward the Sun, the Sun in turn accelerates toward each planet.

Because the Sun is pulling on the planets, why don’t they fall onto it? Conservation of angular momentum provides the answer. Angular momentum is a measure of how much energy is stored in an object due to its rotation and revolution. The details of momentum are presented in Appendix P: Energy and Momentum. As the orbiting planets fall toward the Sun, their angular momentum provides them with motion perpendicular to that infall, meaning that the planets continually fall toward the Sun, but they continually miss it. Because their angular momentum is conserved, planets neither spiral into the Sun nor fly away from it. Angular momentum remains constant unless acted on by an external torque (also defined in Appendix P).

Angular momentum depends on three things: how fast an object rotates or revolves, how much mass it has, and how spread out that mass is. Consider, for example, a twirling ice

#### Focus Question 2-7

Sitting in a moving car, how can you experimentally verify that your body has inertia?

#### Focus Question 2-8

How did people deduce that there is no air (and, hence, no air friction to slow planets down) in space before airplanes or even people-carrying balloons were invented?

#### Focus Question 2-9

If you are on a freely spinning merry-go-round, what will happen to it as you move toward the center?

**FIGURE 2-12 Conservation of Angular Momentum** As skater Sarah Hughes brings her arms and outstretched leg in, she must spin faster to conserve her angular momentum. You can see that motion in her skirt and hair. (Doug Pensinger/Getty Images Sport/Getty Images)



skater. She rotates with a constant mass, practically free of outside forces. Because her angular momentum is therefore conserved, she can change how fast she is spinning by changing how spread out her mass is. According to conservation of angular momentum, as the spread of mass decreases, the rotation rate must increase. When she wishes to rotate more rapidly, she decreases the spread of her mass distribution by pulling her arms and outstretched leg in closer to her body (**Figure 2-12**). In astronomy, we encounter many instances of the same law, as giant objects, such as stars, contract.

We have now reconstructed the central relationships between matter and motion. Scientific explanation of the heliocentric cosmology still requires a force to hold the planets in orbit around the Sun and the moons in orbit around the planets. Newton identified that, too.

More generally, the gravitational force from every object acts to pull every other object directly toward it.

Newton succeeded in formulating a mathematical model that describes the behavior of the gravitational force that keeps the planets in their orbits (presented in Appendix R: Gravitational Force).

**Newton’s Law of Universal Gravitation:** *Two objects attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.*

The inverse square part of this law means that gravitational force decreases with distance. **Table 2-4** gives some examples of the inverse square law. Despite its weakening, the force of gravity from each object extends throughout

2-8 Newton’s description of gravity accounts for Kepler’s laws

Isaac Newton did not invent the idea of gravity. An observant seventeenth-century person would understand that some force pulls things down to the ground. It was Newton, however, who gave us a quantitative description of the action of gravity, or *gravitation*, as it is more properly called. Using his first two laws, Newton showed mathematically that the force acting on each of the planets is directed toward the Sun. He expanded this result to the idea that the nature of the force pulling a falling apple straight down to the ground is the same as the nature of the force on the planets from the Sun.

EXAMPLES OF THE INVERSE SQUARE LAW FOR GRAVITY. Inverse square means the force of gravity decreases as 1/(distance between two objects) <sup>2</sup> .	
Distance between two objects	The gravitational force between two objects compared to when they are a distance of 1 apart
1	1
2	1/4
3	1/9
4	1/16

the universe. Also, an object with twice the mass of another object exerts twice the gravitational force as the less massive object.

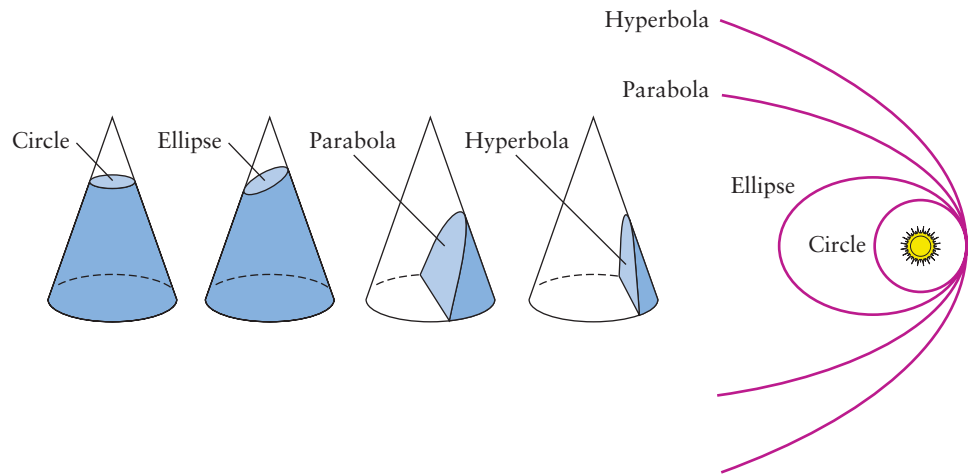
Using his law of gravity along with his three laws stated earlier, Newton found that he could mathematically explain Kepler's three laws. For example, whereas Kepler discovered by trial and error that the period of orbit,  $P$ , and average distance between the Sun and planet,  $a$ , are related by  $P^2 = a^3$ , Newton mathematically derived this equation (corrected by including a tiny contribution due to the mass of the planet, as mentioned earlier). Bodies in elliptical orbits are bound by the force of gravity to remain in orbit.

**6** It seems plausible that astronauts floating in the International Space Station do not feel any force of gravity from Earth, but they do. Orbiting 330 km (approximately 200 mi) above Earth's surface, they feel 90% as much gravitational force from the planet as we do standing on it. They are weightless, however, because as they fall earthward, their angular momentum carries them around the planet at just the right rate to continually miss it. The same effect occurs for all objects in orbit, as shown in the figure that opens this chapter.

Newton also discovered that some objects orbiting the Sun can follow nonelliptical paths. His equations led him to conclude that orbits can also be **parabolas** or **hyperbolas** (Figure 2-13). In both cases, such bodies would make only one pass close to the Sun and then travel out of the solar system, never to return. To date, all of the objects observed in the solar system began their existence in elliptical orbits, but some comets (small bodies of rock and ice) have received enough energy from being pulled by planets or from expelling jets of gas to develop parabolic or hyperbolic orbits.

Using the equations Newton derived, the orbits of the planets and their satellites could be calculated with unprecedented precision. Using his laws, mathematicians showed that Earth's axis of rotation must precess because of the gravitational pull of the Moon and the Sun on Earth's equatorial bulge (recall Figure 1-19). In the spirit of the scientific method, Newton's laws and mathematical techniques were used to predict new phenomena. For example, Edmond Halley was intrigued by historical records of a comet that was sighted about every 76 years. Using his friend Newton's methods, Halley worked out the details of the comet's orbit and predicted its return in 1758. It was first sighted on Christmas night of that year, and to this day the comet bears Halley's name (Figure 2-14).

Perhaps the most dramatic early use of the scientific method with Newton's ideas was its role in the discovery of the eighth planet in our solar system. The seventh planet, Uranus, had been discovered by William Hersch in 1781 during a systematic telescopic survey of the sky. Fifty years later, however, it was clear that Uranus was



**FIGURE 2-13 Conic Sections** A conic section is any one of a family of curves obtained by slicing a cone with a plane, as shown. The orbit of one body around another can be an ellipse, a parabola, or a hyperbola. Circular orbits are possible because a circle is just an ellipse for which both foci are at the same point.

not following the orbit predicted by Newton's laws. Two mathematicians, John Couch Adams in England and Urbain-Jean-Joseph Leverrier in France, independently calculated that the deviations of Uranus from its predicted orbit could be explained by the gravitational pull of a then unknown, more distant planet. Each man predicted that the planet would be found at a certain location in the constellation of Aquarius in September 1846. A telescopic search on September 23, 1846, by German astronomer Johann Galle, revealed Neptune less than  $1^\circ$  from its calculated position. Although sighted with a telescope, Neptune was really discovered with pencil and paper.



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**FIGURE 2-14 Halley's Comet** Halley's Comet orbits the Sun with an average period of about 76 years. During the twentieth century, the comet passed near the Sun twice—once in 1910 and again, as shown here, in 1986. The comet will pass close to the Sun again in 2061. During its last visit, the comet spread more than  $5^\circ$  across the sky, or 10 times the diameter of the Moon. (W. Liller/Large Scale Phenomena Network/NSSDC/NASA)

## Insight Into Science

**Quantify Predictions** Mathematics provides a language that enables science to make quantitative predictions that can be checked by anyone. For example, in this chapter, we have seen how Kepler's third law and Newton's universal law of gravitation correctly predict the motion of objects under the influence of the Sun's gravitational attraction.

It is a testament to Newton's genius that his three laws were precisely the basic ideas needed to understand so much about the natural world. Newton's process of deriving Kepler's laws and the universal law of gravitation helped secure the scientific method as an invaluable tool in our process of understanding the universe. **Figure 2-15** shows some of the effects of gravity at the scales of planets, stars, and galaxies.

## SUMMARY OF KEY IDEAS

**Science: Key to Comprehending the Cosmos**

- The ancient Greeks laid the groundwork for progress in science by stating that the universe is comprehensible.
- The scientific method is a procedure for formulating theories that correctly predict how the universe behaves.
- A scientific theory must be testable, that is, capable of being disproved.
- Theories are tested and verified by observation or experimentation and result in a process that often leads to their refinement or replacement and to the progress of science.
- Observations of the cosmos have led astronomers to discover some fundamental physical laws of the universe.

**Changing Our Earth-Centered View of the Universe**

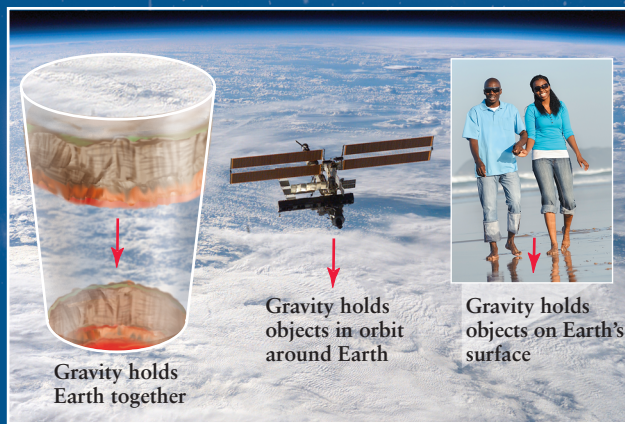
- Common sense (for example, Earth doesn't appear to be moving) led early natural philosophers to devise a geocentric cosmology, which placed Earth at the center of the universe.
- Kepler modified Copernicus's heliocentric (Sun-centered) theory by showing that orbits are elliptical, thereby creating a simplified explanation of planetary motions compared to the geocentric theory.
- The heliocentric cosmology refers to motion of planets and smaller debris orbiting the Sun. Other stars do not orbit the Sun.
- The sidereal orbital period of a planet is measured with respect to the stars and determines the length of the planet's year. A planet's synodic period is measured with respect to the Sun as seen from the moving Earth (for example, from one opposition to the next).

**Kepler's and Newton's Laws**

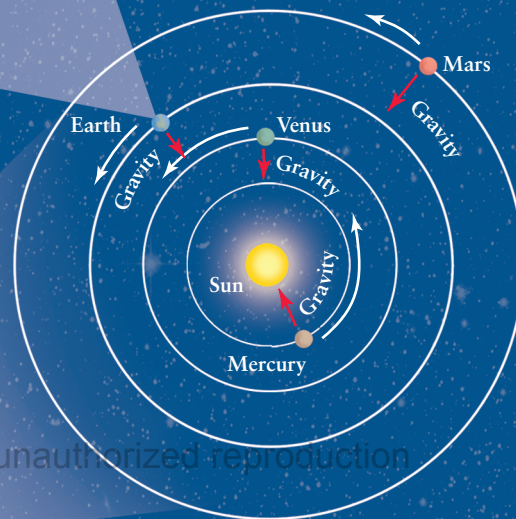
- Ellipses describe the paths of the planets around the Sun much more accurately than do the circles used in previous theories. Kepler's three laws give important details about elliptical orbits.
- The invention of the telescope led Galileo to new discoveries, such as the phases of Venus and the moons of Jupiter, which supported a heliocentric view of the universe.
- Newton based his explanation of the universe on three assumptions, now called Newton's laws of motion. These laws and his law of universal gravitation can be used to deduce Kepler's laws and to describe most planetary motions with extreme accuracy.
- The mass of an object is a measure of the amount of matter in it; weight is a measure of the force with which the gravity of a world pulls on an object's mass when the two objects are at rest with respect to each other (or, equivalently, how much the object pushes down on a scale).
- The path of one astronomical object around another, such as that of a comet around the Sun, is an ellipse, a parabola, or a hyperbola. Ellipses are bound orbits, while objects with parabolic and hyperbolic orbits fly away, never to return.

**WHAT DID YOU THINK?**

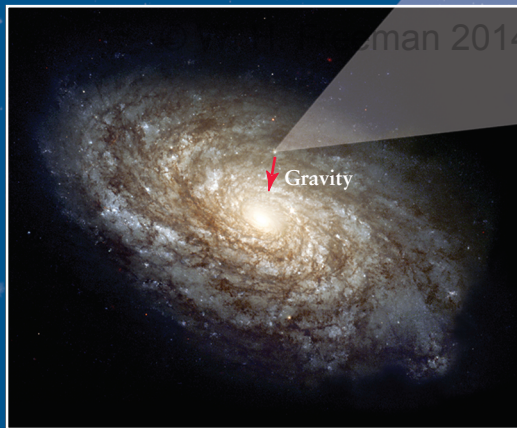
- 1** *What makes a theory scientific?* A theory is an idea or set of ideas proposed to explain something about the natural world. A theory is scientific if it makes predictions that can be objectively tested and potentially disproved.
- 2** *What is the shape of Earth's orbit around the Sun?* All planets have elliptical orbits around the Sun.
- 3** *Do the planets orbit the Sun at constant speeds?* No. The closer a planet is to the Sun in its elliptical orbit, the faster it is moving. The planet moves fastest at perihelion and slowest at aphelion.
- 4** *Do all of the planets orbit the Sun at the same speed?* No. A planet's speed depends on its average distance from the Sun. The closest planet moves fastest, while the most distant planet moves slowest.
- 5** *How does an object's mass differ when measured on Earth and on the Moon?* Assuming the object doesn't shed or collect pieces, its mass is the same on Earth and on the Moon. Its weight, however, is less on the Moon.
- 6** *Do astronauts orbiting Earth feel the force of gravity from our planet?* Yes. They are continually pulled earthward by gravity, but they continually miss it because of their motion around it.



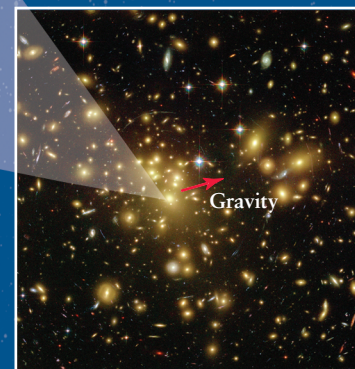
Earth



(Part of) Solar system



Galaxy



Cluster of galaxies

**FIGURE 2-15 Gravity Works at All Scales** This figure shows a few of the effects of gravity here on Earth, in the solar system, in our Milky Way Galaxy, and beyond. The arrow in the cluster of galaxies shows the direction of the force of gravity from one

cluster (bright group of galaxies on the right) on another cluster. (Space station: NASA; couple holding hands: Warren Goldswain/Shutterstock; galaxy: NASA; galaxy cluster: ESA, NASA, J.-P. Kneib [Caltech/Observatoire Midi-Pyrénées] and R. Ellis [Caltech])

### Review Questions

- Who wrote down the equation for the law of gravitation?
  - Copernicus
  - Tycho
  - Newton
  - Galileo
  - Kepler
- Which of the following most accurately describes the shape of Earth's orbit around the Sun?
  - circle
  - ellipse
  - parabola
  - hyperbola
  - square
- Of the following planets, which takes the longest time to orbit the Sun?
  - Earth
  - Uranus
  - Mercury
  - Jupiter
  - Venus
- What is a Sun-centered model of the solar system called?
- How long does it take Earth to complete a sidereal orbit of the Sun?
- How did Copernicus explain the retrograde motions of the planets?
- Which planets can never be seen at opposition? Which planets never pass through inferior conjunction?
- At what configuration (superior conjunction, greatest eastern elongation, etc.) would it be best to observe Mercury or Venus with an Earth-based telescope? At what configuration would it be best to observe Mars, Jupiter, or Saturn? Explain your answers.
- What are the synodic and sidereal periods of a planet?
- What are Kepler's three laws? Why are they important?
- In what ways did the astronomical observations of Galileo support a heliocentric cosmology?
- How did Newton's approach to understanding planetary motions differ from that of his predecessors?
- What is the difference between mass and weight?
- Why was the discovery of Neptune a major confirmation of Newton's universal law of gravitation?
- Why does an astronaut have to exert a force on a weightless object to move it?

### Got It?

- A comet coming inward from the Kuiper belt, a region of Sun-orbiting debris out beyond the orbit of Neptune, experiences a gravitational force from the Sun. Does the presence of the planets affect the comet's orbit? Explain your reasoning.
- How would the weight of an astronaut on the Moon compare to her weight on Earth?
- How would the mass of an astronaut on the Moon compare to his mass on Earth?
- An astronomer observes a new comet and calculates that it will exit the solar system and not return. Which of the following best describes the path of the comet?
  - a nearly straight line
  - a circle
  - an ellipse
  - a hyperbola
  - some other shape

### Advanced Questions

- From the definition  $KE = \frac{1}{2}mv^2$ , derive the equation  $KE = p^2/2m$ , as discussed in Appendix P.
- Is it possible for an object in the solar system to have a synodic period of exactly 1 year? Explain your answer.
- Describe why there is a systematic decrease in the synodic periods of the planets from Mars outward, as shown in Table 2-1.
- Make diagrams of Jupiter's phases as seen from Earth and as seen from Saturn.
- In what direction (left or right, eastward or westward) across the celestial sphere do the planets normally appear to move as seen from Australia? In what direction is retrograde motion as seen from there?
- The dictionary defines astrology as "the study that assumes and attempts to interpret the influence of the heavenly bodies on human affairs." Based on what you know about scientific theory, is astrology a science? Why or why not? Feel free to further explore astrology, if you wish, before answering this question.

### Discussion Questions

- Which planet would you expect to exhibit the greatest variation in apparent brightness as seen from Earth? Explain your answer.
- Use two thumbtacks (or pieces of tape), a loop of string, and a pencil to draw several ellipses. Describe how the shapes of the ellipses vary as you change the distance between the thumbtacks.