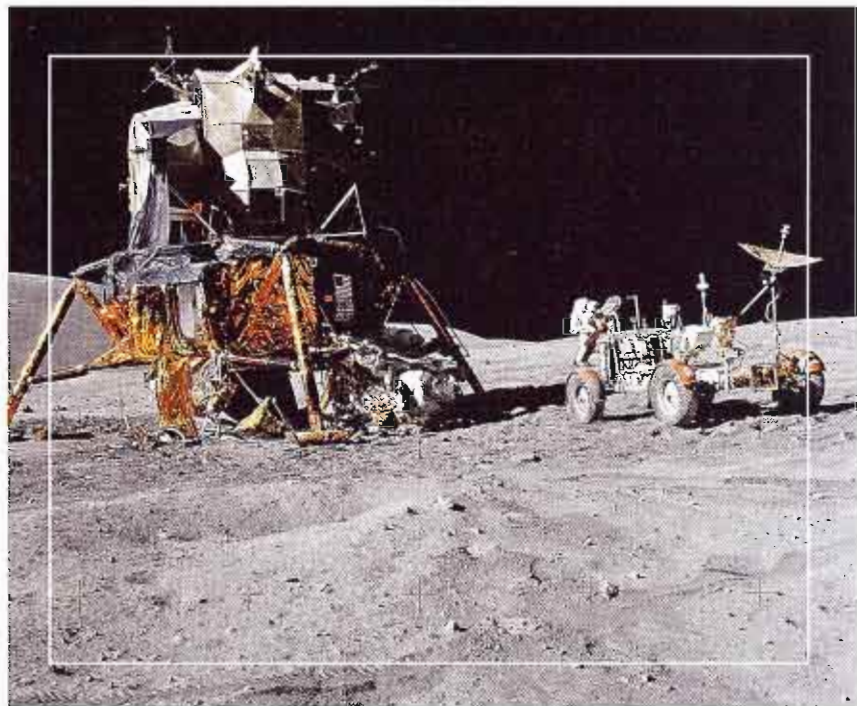


# Gravitation and the Motion of the Planets

Gravitation, the only universal force of attraction in nature, holds objects onto surfaces and in orbit. Our Moon, smaller and less massive than Earth, has only  $1/6$  the gravitational force that we feel here. Therefore, astronauts as shown in this *Apollo 15* image, can easily manage the spacesuits they wore. On Earth the suits weighed 180 lb, while on the Moon they were only 30 lb. (NASA)



R I V U X G

## 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 much force does it take to keep an object moving in a straight line at a constant speed?
- 6 How does an object's mass differ when measured on Earth and on the Moon?
- 7 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.*



**S**cience enables us to understand and manipulate an awesome range of nature's properties. Scientists are a lot like detectives, and the process they follow when trying to explain

scientific phenomena has a good deal in common with the activities of sleuths as they try to solve mysteries. For example, an investigator might suddenly realize that his prime suspect, the person around whom his whole case has revolved, could not have committed the crime because he was actually baking a soufflé at the time. Similarly, the astronomers and mathematicians who studied the motions of heavenly bodies made their biggest leap forward when the evidence forced them to look beyond the suspect they believed to be at the center of everything—Earth.

This chapter traces how we moved from an Earth-centered view of the universe to a Sun-centered one and how we came to understand the physical principles by which the basic motions of the universe operate. The process of this discovery initially involved the efforts of a few determined scientist-sleuths. To unravel the mysteries that puzzled them—such as why planets appear at times to change direction on the celestial sphere or why the assumption that Earth is the center of the universe kept failing to predict the locations of certain bodies—they used careful observations and a willingness to question their own and others' assumptions.

The groundwork for modern science was set down by Greek mathematicians and philosophers beginning around 2500 years ago, when Pythagoras and his followers began using mathematics to describe natural phenomena. About 200 years later, Aristotle asserted that the universe is comprehensible: It is governed by regular laws. The Greeks typically did not, however, perform experiments to test their ideas, an essential part of the scientific method used today. Nevertheless, they were among the first to leave a written record of their ideas, allowing succeeding generations to develop, criticize, and test their conclusions.

These Greek ideas, rediscovered in the seventeenth century, led to the development of the scientific method

of examining, understanding, and predicting how things work. Science provides explanations for activities and events, and it makes predictions about things that have not yet happened or that have not yet been observed. These are incredibly powerful tools that enable us to understand what we see without having to accept events on faith or to fear that things like the force of gravity will change on a whim. Science simplifies life and takes some of the uncertainty out of the world.

Consider the topic of this chapter, our understanding of gravity. Until Isaac Newton made the conceptual leap that the force holding Earth in orbit around the Sun is the same force that holds us onto the Earth, these two effects were considered to be separate and unrelated. Once they were connected, and an equation was written to describe the behavior of Earth and of falling objects, people had, for the first time, the ability to predict the future motion of projectiles and other falling objects reliably. Albert Einstein (Chapter 14) plumbed the depths of gravitational behavior even further, developing equations that make even more accurate predictions. The fundamentals of gravity we study here lead to our understanding of its effects on the universe, including how it causes stars and planets to form (Chapter 6), enables stars to shine (Chapter 10), and holds galaxies together (Chapter 15), among many other things.

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## In this chapter you will discover

- what makes a theory scientific
  - the scientific revolution that dethroned Earth from its location at the center of the universe
  - Copernicus's argument that the planets orbit the Sun
  - why the direction of motion of the planets on the celestial sphere sometimes appears to change
  - that Kepler's determination of the shapes 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

Understanding how nature works enables us to manipulate the matter and energy that comprise our environment and thereby to create new things to make our lives better. Improvements in technology lead, in turn, to better research equipment, enabling us to make even deeper discoveries about space, time, matter, energy, and the relationships among them. This spiral of understanding and application began centuries ago. In this chapter we will explore the nature of science and use it to see how gravity keeps planets and other objects orbiting the Sun and moons orbiting their respective planets.

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

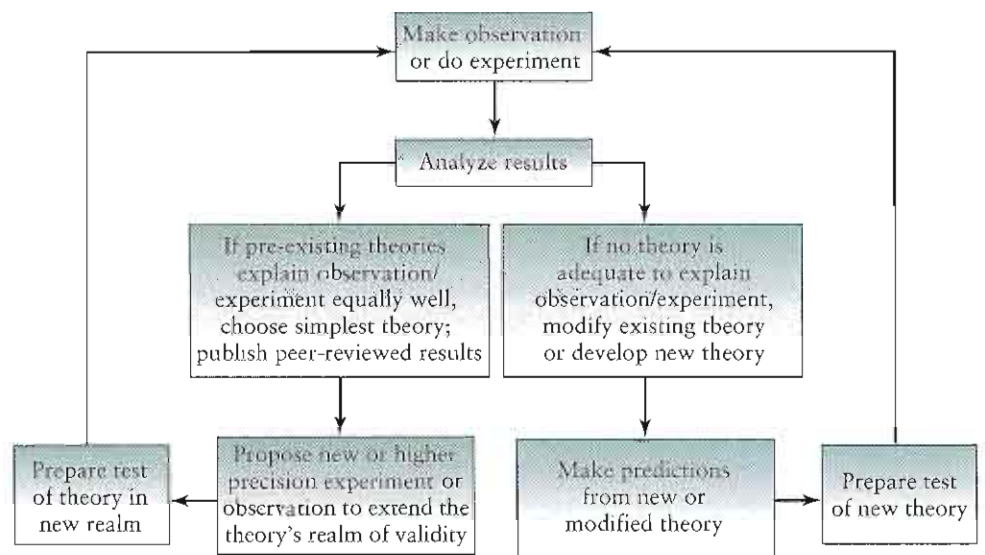
Science is actually two things. First, it is a body of knowledge that we acquire by observations and experiments. The details of the motions of the Moon, planets, and Sun on the celestial sphere, described in Chapter 1, are examples of that knowledge. While nature can be discussed descriptively, as it is for the most part in this book, science also provides mathematical equations that quantify the effects being studied.

Second, science is a process for gaining more knowledge 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**, and it 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 by people making observations or doing experiments. For example, the observation that some objects (e.g., planets) move along the celestial sphere, while others (stars) remained fixed on it, demanded explanation. The results of observations or experiments are compared with the predictions of a preexisting theory that is supposed to explain them. If the new data and old ideas are not consistent, then a *hypothesis* that modifies or replaces the existing explanation is proposed. Hypotheses on related topics that make accurate predictions are incorporated together as a scientific theory (often just called a theory).

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 lead to rigorous predictions. The word *theory* in science has a very different connotation. It is an explanation of observations or experimental results that can be described quantitatively and tested formally. The mathematical description of 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.

As just noted, to be considered scientific, a theory must make *testable* predictions that can be verified using new observations and experiments. Testing is a crucial aspect of the scientific method, which 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.

Scientists who develop new or more accurate models are going where no person has gone before. Many of them find this process of discovery as satisfying as an artist creating a masterpiece, an athlete breaking a world record, or an astronaut going into space. Similarly,



**FIGURE 2-1 The Scientific Method** This flow chart shows the basic processes 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 same aspect of science and willing to learn the tools of that science can participate in the adventure. (© Neil F. Comins)

scientists who make observations or do experiments that reveal previously unknown facts about nature often have similar reactions to their discoveries.

### INSIGHT INTO SCIENCE

**Science Is Inclusive** Science is intended as an inclusive endeavor. 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.

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 disproved by observations and thus qualifies as a scientific theory. The idea that Earth was created in six days cannot be tested, much less disproved. It is not a scientific theory, but rather a matter of faith.

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 the vicinity of a black hole, where matter is especially dense. In this case, 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.

Give an example of one scientific hypothesis and one nonscientific hypothesis.

### 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 independently. 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.

Science also strives to explain as many things as possible with as few theories as possible. 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.

### INSIGHT INTO SCIENCE



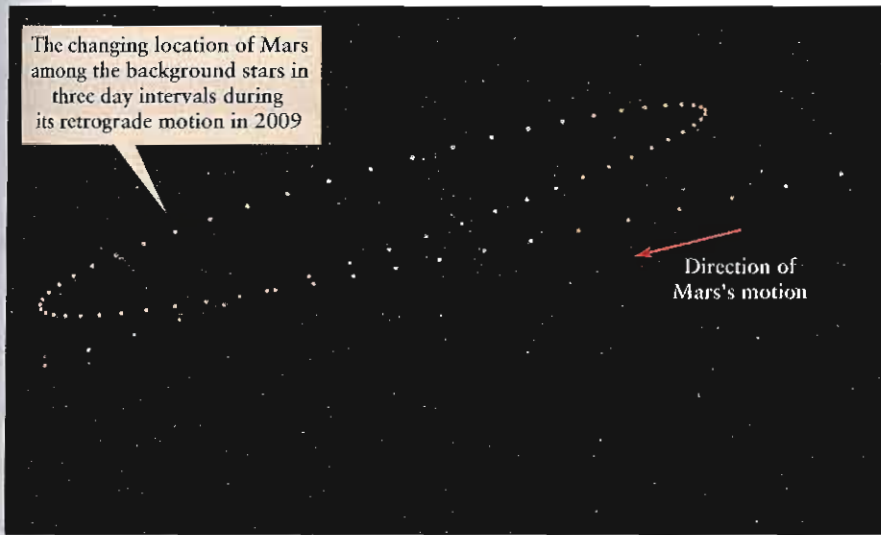
**Keep It Simple** When several competing theories describe the same concepts with the same accuracy, scientists choose the simplest one—namely, the one that contains the fewest unproven assumptions. That basic tenet, formally expressed by William of Occam in the fourteenth century, is known as Occam's razor. Indeed, the original form of the Sun-centered cosmology, which we are about to explore, was appealing because it made the same predictions within a simpler model than did the Earth-centered cosmology. *Remember Occam's razor.*

While the vast majority of scientists carefully and scrupulously follow the rules of scientific research, we acknowledge that some experiments are run poorly. Some scientists have ignored experimental data or observations that don't mesh with cherished beliefs or even fudged data or stolen data from others. Virtually all of these oversights and misdeeds are eventually discovered because most theories and their predictions are tested by several independent researchers.

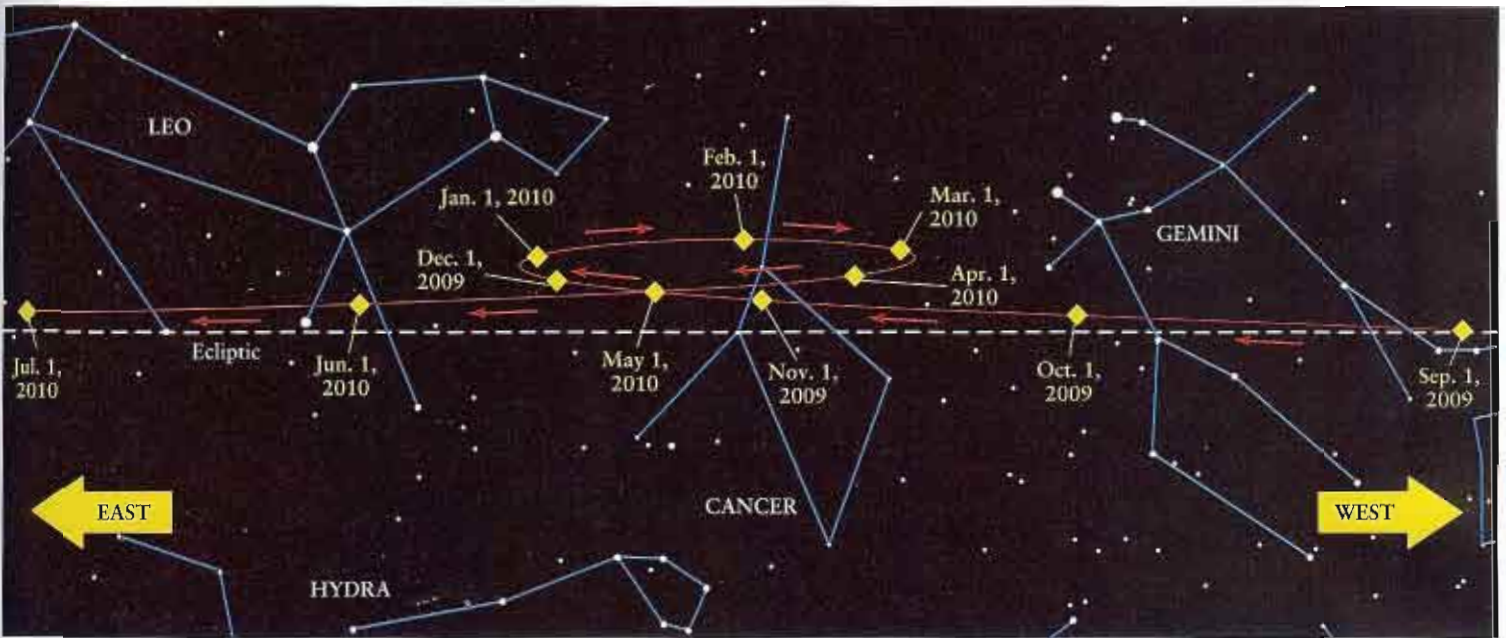
The scientific method can be summarized in six words: *observe, hypothesize, predict, test, modify, economize*. I urge you to watch for applications of the scientific method throughout this book. Our first encounter with it is the discovery that Earth orbits the Sun.

## 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



**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, the same time interval from September 2009 through June 2010, is plotted in cartoon form. From December 23, 2009, through March 12, 2010, Mars is in retrograde motion. The retrograde loop is sometimes north of the normal path and sometimes south of it (see Figure 2-3).



motion of the celestial sphere, they believed that the Sun, the Moon, the stars, and the planets revolve 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 for more than 2000 years.

## 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**. Occasionally, however, a planet seems to stop and then back up for several weeks or months. This reverse movement (to the west relative to the background stars) is called **retrograde motion**. Both direct and retrograde motions are best observed by plotting or photographing the nightly position of a planet against the background stars over a long period (Figure 2-2a and b).

All planetary motions on the celestial sphere are much slower than the apparent daily movement of the entire sky caused by Earth’s rotation, and so they are superimposed on it. Therefore, the planets always rise in the eastern half of the sky and set in the western half, as the stars do.

## Earth-centered Universe

As we move through the twenty-first century, 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. These facts have become part of our understanding of the motions of the heavenly bodies and we are taught these things from the time we are children.

Psychologists call this background information that we use to help explain things a *conceptual framework*. Any 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.

Our ancestors possessed a different conceptual framework for understanding the cosmos. They did not know that Earth rotates. They did not know that the then-mysterious force that held them to the ground is the same force that attracts Earth to the Sun and the Moon to Earth. They did not know that the Sun is a star, just like the fixed points of light in the sky, and they did not know any of the other laws of motion that we take for granted.

Because they did not feel Earth move under their feet, or see any other indication that Earth is in motion, our forebears sensed nothing to support the belief that we are in motion. 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, there-

fore, the conceptual frameworks that we possess are less consistent with common sense than those held in the past. Studying science helps us develop intuition that is consistent with the actual workings of nature.

**Geocentric Explanation of the Planets' Retrograde Motion** The early Greeks 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 ideas was expounded by the last of the great ancient Greek astronomers, Ptolemy, who lived in Alexandria, Egypt, 1900 years ago. His basic concepts are sketched in the accompanying figure. 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 it and the planet on it revolve in the same direction (counterclockwise).

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 GD2.1a). 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 seems to move to the right (westward) among the stars for a few weeks or months (Figure GD2.1b). This concept of epicycles and deferents enabled Greek astronomers to explain the retrograde loops of the planets.

Using the wealth of astronomical data in the library at Alexandria, including records of planetary positions

The effort to understand planetary motion in a geocentric cosmology resulted in an increasingly contrived and complex model, especially in explaining retrograde motion (see *Guided Discovery: Earth-Centered Universe*). The ancient Greek astronomer Aristarchus 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 just because the faster-moving Earth overtakes and passes 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 don't. In fact, the Sun and the bodies that orbit the Sun all orbit the center of our Milky Way Galaxy.)

Because simplicity and accuracy are hallmarks of science, the complex geocentric model eventually gave way to the simpler, more elegant heliocentric cosmology, but dethroning the geocentric model did not occur immediately. In the first place, Earth just does not seem

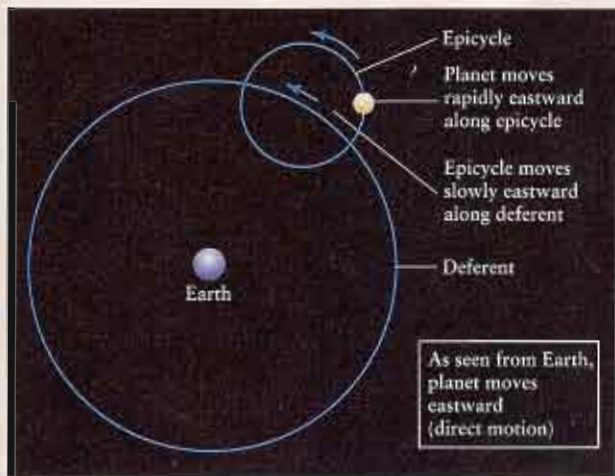
Why do you think Mars is seen sometimes above the ecliptic and sometimes below it?

## The Earth-centered Universe (continued)

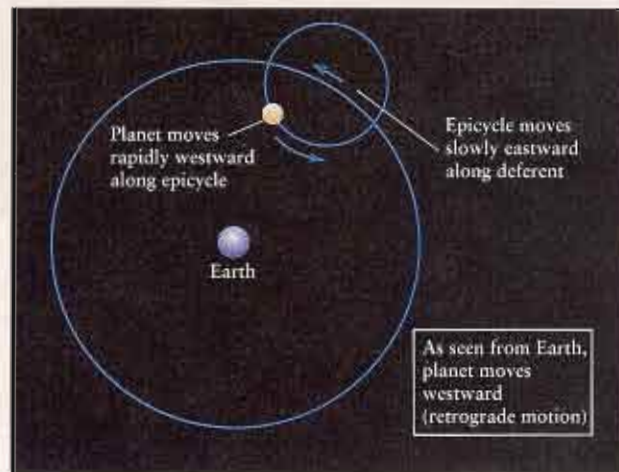
covering hundreds of years, Ptolemy deduced the sizes of the epicycles and deferents and the rates of revolution needed to produce the recorded paths of the planets. After years of arduous work, Ptolemy assembled his calculations in the *Almagest*, in which the positions and paths of the Sun, Moon, and planets were described with unprecedented accuracy. In fact, the *Almagest* was so successful that it became the astronomer's bible. For more than 1000 years, Ptolemy's cosmology endured as a useful description of the workings of the heavens.

Eventually, however, the commonsense explanation of the Earth-centered cosmology began to go awry.

Errors and inaccuracies that were unnoticeable in Ptolemy's day compounded and multiplied over the years, especially errors due to precession, the slow change in the direction of Earth's axis of rotation. Fifteenth-century astronomers made some cosmetic adjustments to the Ptolemaic system. However, the system became less and less satisfactory as more fanciful and arbitrary details were added to keep it consistent with the observed motions of the planets. After Newton's time, scientists knew that orbital motion required a force to be acting on the body. However, nothing in Ptolemy's epicycle theory produced such a force.



a



b



**FIGURE GD2-1 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 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.

to move! This observation, along with strict geocentric religious teachings and the human desire to be at the center of everything, outweighed the simpler plan proposed by Aristarchus. Not until 1300 years later did anyone seriously reconsider the advantages of a heliocentric cosmology.

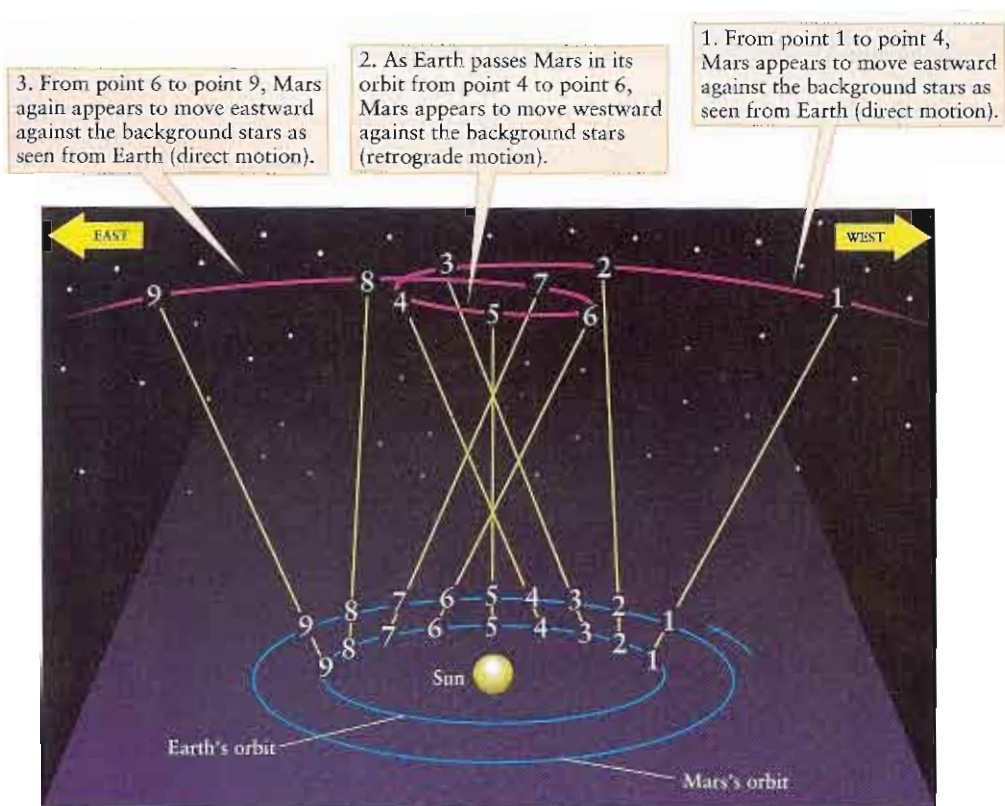
### 2-3 Copernicus devised the first comprehensive heliocentric cosmology

Over the centuries, increasingly accurate observations of the planets' locations revealed errors in the predic-

tions 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 (see *Guided Discovery: Astronomy's Foundation Builders*) was motivated by an effort to simplify the celestial scheme.



After assuming that the planets orbit the Sun rather than Earth, Copernicus, through observations, determined which



**FIGURE 2-3 A Heliocentric Explanation of Planetary 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.

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. 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 can occur only if Earth comes between the Sun and a planet. Copernicus therefore concluded (correctly) that the orbits of Mars, Jupiter, and Saturn lie outside Earth's orbit.

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 is about  $28^\circ$  for Mercury and about  $47^\circ$  for Venus (Figure 2-4). When either Mercury or Venus rises before the Sun, it 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, it 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 is especially true of Mercury, often making it 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 them is located behind the Sun, as seen from Earth, it is said to be in **conjunction**. When it is opposite the Sun in the sky, the 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 your study of the Moon in Chapter 1 that the sidereal period of orbit is the true orbital period of any astronomical body. A planet's **sidereal period** is the time it would take an observer fixed at the Sun's location watching that planet move through the background stars to go from one point on the celestial sphere, around the sphere, and back to that same point again. The sidereal period is the length of a year for each planet.

## GUIDED DISCOVERY

## Astronomy's Foundation Builders

In the two centuries between 1500 and 1700, human understanding of the motion of celestial bodies and the nature of the gravitational force that keeps them in orbit surged forward as never before. Theories related to this subject were developed by brilliant thinkers, whose work established and verified the heliocentric model of the solar system and the role of gravity.



(E. Lessing/Art Resource)

**Nicolaus Copernicus (1473–1543)** Copernicus, the youngest of four children, was born in Torun, Poland. He pursued his higher education in Italy, where he received a doctorate in canon law and studied medicine. Copernicus developed a heliocentric theory of the known universe and just before his death in 1543 published this work under the title *De Revolutionibus Orbium Coelestium*. His revolutionary

theory was flawed in that he assumed that the planets had circular orbits around the Sun. This was corrected by Johannes Kepler.



(Painting by Jean-Leon Huens, courtesy of National Geographic Society)

**Tycho Brahe (1546–1601)** and **Johannes Kepler (1571–1630)** Tycho (depicted within the portrait of Kepler) was born to nobility in the Danish city of Knudstrup, which is now part of Sweden. At age 20 he lost part of his nose in a duel and wore a metal replacement thereafter. In 1576 the Danish king Frederick II built Tycho an astronomical observatory that Tycho named Uraniborg (after Urania, Greek muse of astronomy). Tycho rejected both Copernicus's heliocentric theory and the Ptolemaic geocentric system. He devised a halfway theory called the *Tychonic system*. According to Tycho's theory, Earth is stationary, with the Sun and Moon revolving around it, while all the other planets revolve around the Sun. Tycho died in 1601.

Kepler was educated in Germany, where he spent three years studying mathematics, philosophy, and theology. In 1596, Kepler published a booklet in which he attempted to mathematically predict the planetary

orbits. Although his theory was altogether wrong, its boldness and originality attracted the attention of Tycho Brahe, whose staff Kepler joined in 1600. Kepler deduced his three laws from Tycho's observations.



(Art Resource)

**Galileo Galilei (1564–1642)** Born in Pisa, Italy, Galileo studied medicine and philosophy at the University of Pisa. He abandoned medicine in favor of mathematics. He held the chair of mathematics at the University of Padua, and eventually returned to the University of Pisa as a professor of mathematics. There Galileo formulated his famous law of falling bodies: All objects fall with the same acceleration regardless of their

weight. In 1609 he constructed a telescope and made a host of discoveries that contradicted the teachings of Aristotle and the Roman Catholic Church. He summed up his life's work on motion, acceleration, and gravity in the book *Dialogues Concerning the Two Chief World Systems*, published in 1632.



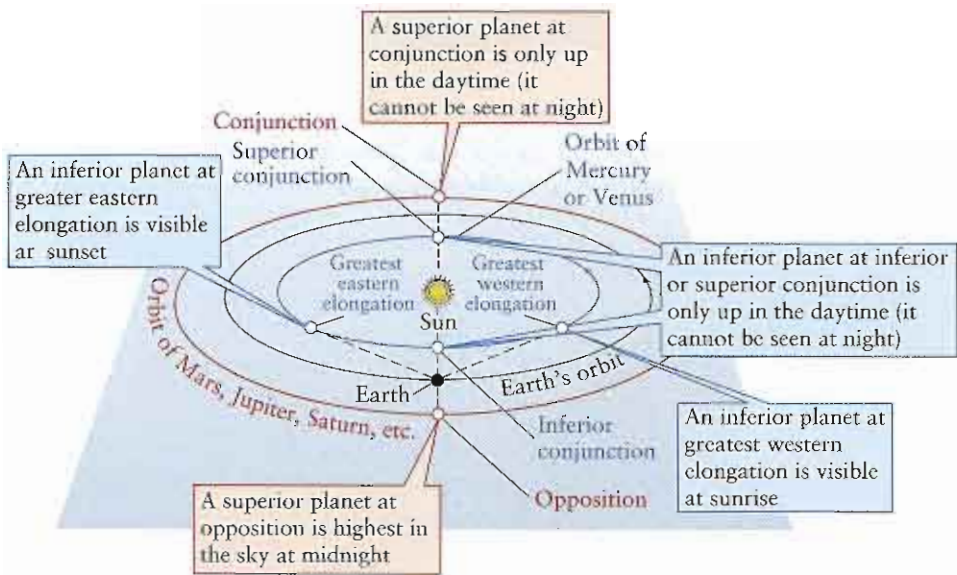
(National Portrait Gallery, London)

**Isaac Newton (1642–1727)** Newton delighted in constructing mechanical devices, such as sundials, model windmills, a water clock, and a mechanical carriage. He received a bachelor's degree in 1665 from the University of Cambridge. While there, he began developing the mathematics that later became calculus (developed independently by the German Gottfried Leibniz). While pursuing experiments in optics, Newton constructed a

reflecting telescope and also discovered that white light is actually a mixture of all colors. His major work on forces and gravitation was the tome *Philosophiae Naturalis Principia Mathematica*, which appeared in 1687. In 1704, Newton published his second great treatise, *Opticks*, in which he described his experiments and theories about light and color. Upon his death in 1727, Newton was buried in Westminster Abbey, the first scientist to be so honored.

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. It can be from one opposition to the

next, for example, or from one conjunction to the next (Figure 2-5). It tells us, among other things, when to expect a planet to be closest to Earth and, therefore, most easily studied.



**FIGURE 2-4 Planetary Configurations** Key points along a planet's orbit have names, as shown. These points identify specific geometric arrangements between Earth, another planet, and the Sun. Knowing where a planet is with respect to the Sun helps astronomers know when and where to look for the planet.

**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*.

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

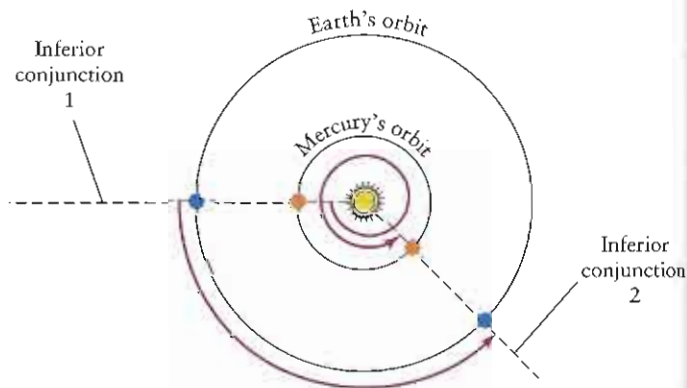
was published in 1543, the year of his death. His great insight was the conceptual simplicity of a heliocentric cosmology compared to geocentric views, especially in explaining retrograde motion. However, Copernicus incorrectly assumed that the planets travel along circular paths around the Sun. Without using epicycles similar to those used in geocentric theory (Figure GD2.1), many of his predictions were no more accurate than those of the earlier theory! As we will see shortly, by changing the shape of the orbits, Kepler was able to do away with epicycles and make even more accurate predictions than either the geocentric or original Copernican theory.

**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 it faded from view.



Modern astronomers recognize this event as a supernova explosion, the violent death of a certain type of star (see Chapter 13). In the sixteenth century, however, the prevailing opinion was quite different. Teachings dating back to Aristotle and Plato argued that the heavens were



**FIGURE 2-5 Synodic Period** The time between consecutive conjunctions of Earth and Mercury is 116 days. 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 exterior 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

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 (see *Guided Discovery: Astronomy’s Foundation Builders*) 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).

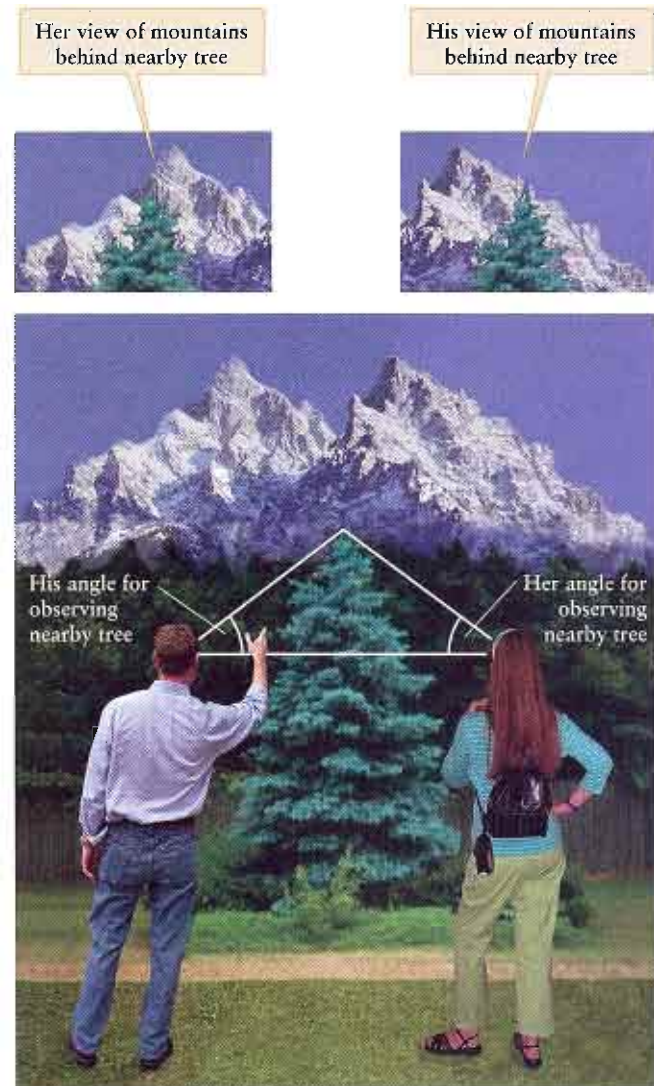
Tycho reasoned as follows: If the new star is nearby, its position should shift against the background

**TABLE 2-2** Average Distances of the Planets from the Sun

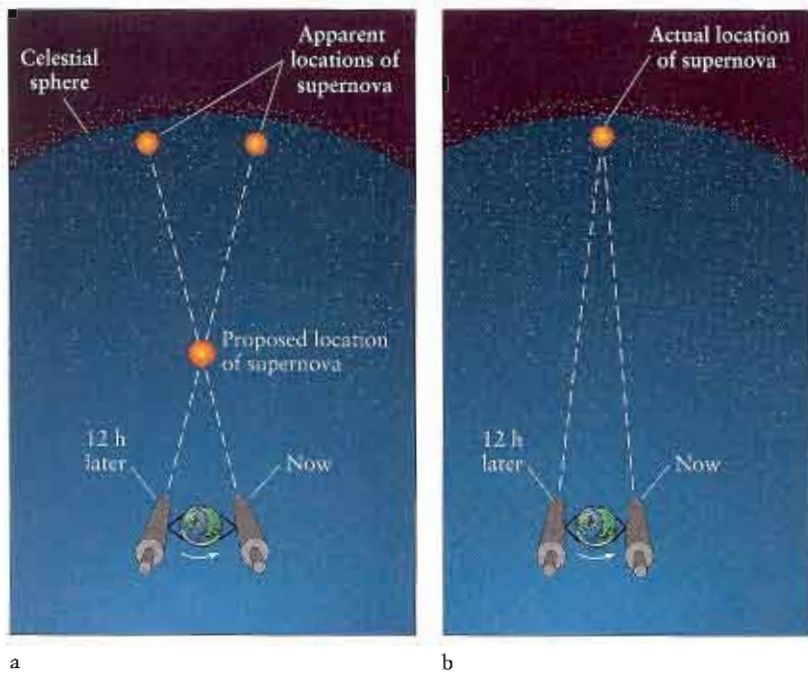
	Measurement (AU)	
	By Copernicus	Modern
Mercury	0.38	0.39
Venus	0.72	0.72
Earth	1.00	1.00
Mars	1.52	1.52
Jupiter	5.22	5.20
Saturn	9.07	9.54
Uranus	Unknown	19.19
Neptune	Unknown	30.06

stars over the course of a night (Figure 2-7a). His careful observations, done in the spirit of the scientific method, failed to disclose 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 Stella Nova* (On the New Star), published in 1573.

Tycho’s astronomical records were soon to play an important role in the development of a heliocentric cosmology. From 1576 to 1597, Tycho made comprehensive observations, measuring planetary positions with an accuracy of 1 arcmin, about as precise as is possible with the naked eye. [Arcminute (arcmin) is defined in *An*



**FIGURE 2-6 Parallax.** Nearby objects are viewed at different angles from different places. These objects also appear to be in different places with respect to more distant objects when viewed at the same time by observers located at different positions. Both effects are called parallax, and they are used by astronomers, surveyors, and sailors to determine distances. (Tobi Zousner)



**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.

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. He published this discovery 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 a 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 approaches being 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 (circular orbit) to just under 1.0 (nearly 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.

Tycho's observations also showed Kepler that planets do not move at uniform speeds along their orbits. Rather, a planet moves most rapidly 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, 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.

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

*Astronomer's Toolbox 1-1.*] Upon Tycho's death in 1601, most of these invaluable records were given to his gifted assistant Johannes Kepler (see *Guided Discovery: Astronomy's Foundation Builders*).

## KEPLER'S AND NEWTON'S LAWS



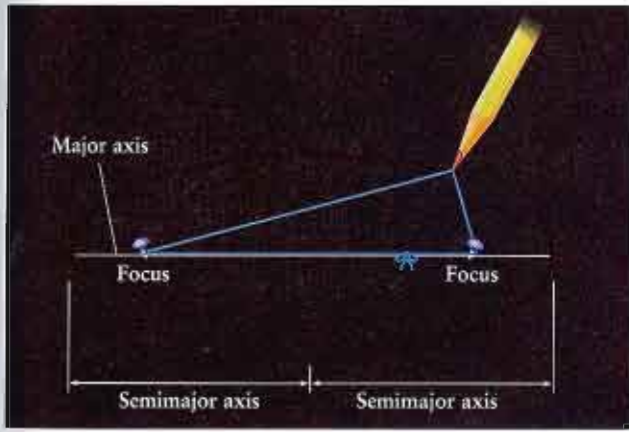
Until Kepler's time, astronomers had assumed that heavenly objects move in circles. For philosophical and aesthetic reasons, circles were considered the most perfect and most harmonious of all geometric shapes. However, using circular orbits failed to yield accurate predictions for the positions of the 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

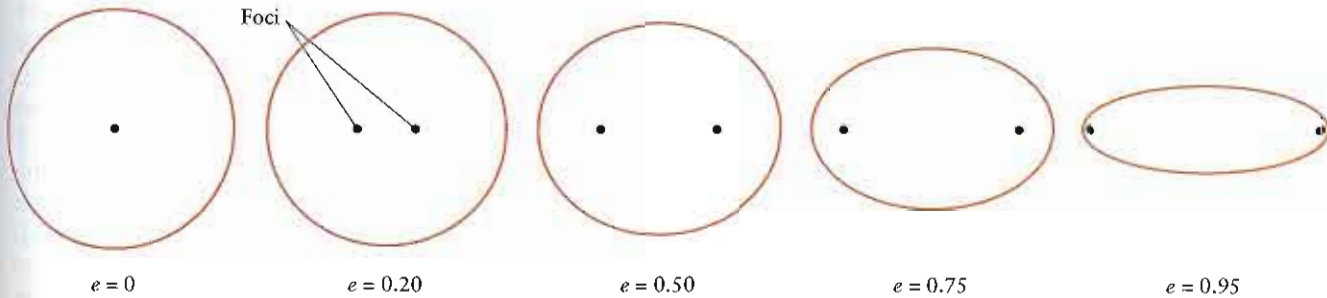
You can draw an ellipse as shown in Figure 2-8a. Each thumbtack is at a focus (plural foci). The longest diameter (major axis) across an ellipse passes through both foci. Half of that distance is called the *semimajor axis*. In astronomy, the length of the semimajor axis is also the average distance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



© 1980 Sidney Harris



**FIGURE 2-8 Ellipses** (a) The construction of an ellipse: At all places along an ellipse, the sum of the distances to the two foci is a constant. An ellipse can be drawn with a pencil, a loop of string, and two thumbtacks, as shown. If the string is kept taut, the pencil traces out an ellipse. The two thumbtacks are located at the two foci of the ellipse. (b) A series of ellipses with different eccentricities,  $e$ . Eccentricities range between 0 (circle) to just under 1.0 (almost a straight line). Note that all eight planets have eccentricities less than 0.21.



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 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. It 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 in Earth years and  $a$  represent the length of the semimajor axis measured in astronomical units (AU). One astronomical unit is the average distance from Earth to the Sun. It is commonly used in discussing distances to various objects in the solar system, because no powers of ten need be used with it, as they

would if distances between planets were referred to in kilometers or miles. (See *An Astronomer's Toolbox 2-1* for more details of astronomical distance units.) Now we can write Kepler's third law as

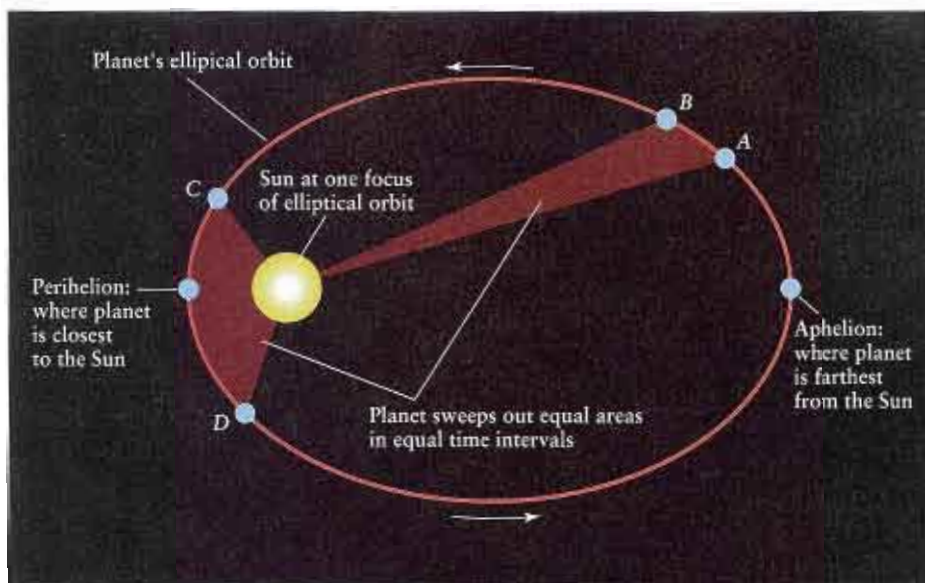
$$P^2 = a^3$$

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 Tables 2-1 and 2-2, we can demonstrate Kepler's third law as shown in Table 2-3.

When Newton derived Kepler's third law using the law of gravitation, discussed later in this chapter, he discovered that the mass of the planet affects the period of its orbit around the Sun. However, this effect of the planet's mass is vanishingly 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 the masses into account. When calculating the motion of pairs of stars orbiting each other, the effects of the masses must be taken into account, as described in *An Astronomer's Toolbox 11-4*.

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

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?



**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 burgandy-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.

## 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

the apparent size of Venus as seen through his telescope was related to the planet's phase (Figure 2-10). Venus appears smallest at gibbous phase and largest at crescent phase. These observations were a big chink in the geocentric cosmology's armor, as it could not explain why Venus has phases or changes size, but a heliocentric cosmology explains both. Galileo's observations, therefore, supported the conclusion that Venus orbits the Sun, not the Earth.

In 1610, Galileo (see *Guided Discovery: Astronomy's Foundation Builders*) also discovered four moons near Jupiter. Today, in honor of their discoverer, these are called the Galilean moons (or satellites, another term for moon). Galileo concluded that the moons orbit Jupiter because they move across from one side of the planet to the other.

Confirming observations were made in 1620 (Figure 2-11). These observations all provided further proof 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." In 1992, Pope John Paul II stated that the church erred in condemning him.

A major stumbling block prevented seventeenth-century thinkers from accepting Kepler's laws and Galileo's conclusions about the heliocentric cosmology.

**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

## AN ASTRONOMER'S TOOLBOX 2-1

## 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 Paris to London 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 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). 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.

$$1 \text{ ly} \approx 9.46 \times 10^{12} \text{ km} \approx 63,000 \text{ AU}$$

The space between the planets, stars, and galaxies are nearly ideal vacuums. One light-year is roughly equal to six trillion miles. Proxima Centauri, the closest star to Earth, other than the Sun, is just over 4.2 light-years 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. 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  $1/3600^\circ$  (called 1 arcsec), you have reached a distance that astronomers call 1 parsec, as shown in the figure below. 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 taste.

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:

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

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

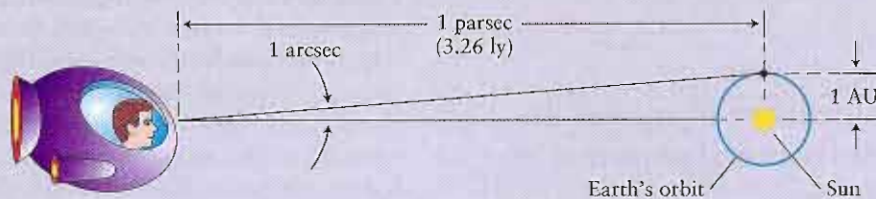
$$1 \text{ kpc} = 10^3 \text{ pc}$$

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

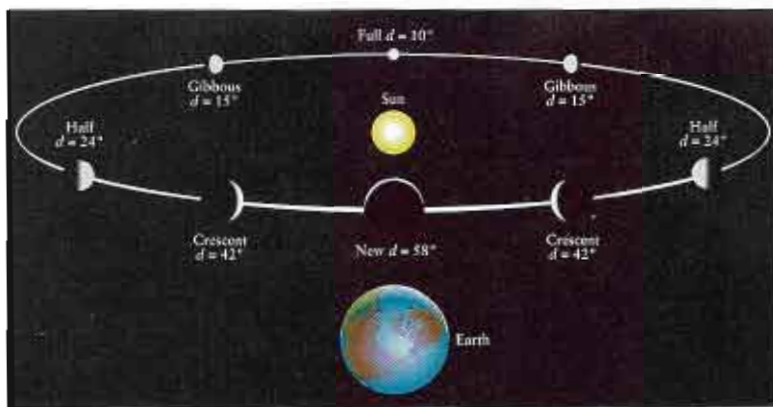
For example, the distance from Earth to the center of our Milky Way Galaxy is about 8.6 kpc, and the rich cluster of galaxies in the direction of the constellation Virgo is 20 Mpc away.

**Try these questions:** The nearest star (other than the Sun) is 4.22 ly away. How many miles away is it? How many kilometers? How many parsecs?

(Answers appear at the end of the book.)



**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.



**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. 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.

Once anything on Earth is put in motion, it quickly comes to rest. Why don't the planets orbiting the Sun stop, too?

What is the shape of the orbit around Earth of the International Space Station?

The scientific method clarified all of the mysteries about planets and orbits in the form of equations and laws developed by the brilliant and eccentric (for example, he believed in alchemy) scientist Isaac Newton, who 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 proofs of the heliocentric cosmology.

### 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, in 1665, when Newton derived them with his mathematical expression for gravitation, the force that holds the planets in their orbits.

## 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 (see *Guided Discovery: Astronomy's Foundation Builders*) 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, 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 don't cancel each other out, then there is a "net" external force acting on it. This is the same as saying that there is an unbalanced external force. Here is an example: If you put a soccer ball between your hands and press on it so that it doesn't move, your hands represent a balanced pair of forces acting on the ball. In that case, you are exerting no net external force on it. 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 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 that there must be an outside force acting on the planets to continually change their directions and keep them in orbit. If there were no



b

R T V U X 6

**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, taken by amateur astronomer C. Holmes, shows 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. (Courtesy of C. Holmes)

force acting on them, they would move away from the Sun along straight-line paths at constant speeds. Because this does not happen, Newton concluded that some force confines the planets to their elliptical orbits. As we shall see, that force is 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, or a change in direction are all forms of acceleration.

Suppose 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.

**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

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

The mass of an object is a measure of the total number of particles that it contains and is expressed in units of kilograms. For example, the mass of the Sun is  $2 \times 10^{30}$  kg, the mass of a hydrogen atom is  $1.7 \times 10^{-27}$  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.

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

## Energy and Momentum

Scientists identify two types of energy that are available to any object. The first, called **kinetic energy**, is associated with the object's motion. For speeds much less than the speed of light, we can write the amount of kinetic energy, KE, of an object as

$$KE = \frac{1}{2}mv^2$$

where  $m$  is the object's mass and  $v$  is its speed. Kinetic energy is a measure of how much work the object can do on the outside world or, equivalently, how much work the outside world has done to give the object this speed.

**Work** is also a rigorously defined concept that often is at odds with our intuition. It is defined as the product of the force,  $F$ , acting on an object and the distance,  $d$ , over which the object moves in the direction of the force:

$$W = Fd$$

For example, if I exert a horizontal force of 50 N (N is the unit newtons and is the metric unit of force) and thereby move an object 10 m in that direction, then I have done  $50 \text{ N} \times 10 \text{ m} = 500 \text{ J}$  of work. (I have used the relationship that 1 newton  $\times$  1 meter = 1 joule.)

The second type of energy is called **potential energy**. It represents how much energy is available to an object as a result of its location in space. For example, if you hold a pencil above the ground, the pencil has potential energy that can be converted into kinetic energy by Earth's gravitational force. How does that conversion get underway? Just let go of the pencil.

There are various kinds of potential energy, such as the potential energy stored in a battery and the potential energy stored in objects under the influence of gravity. We will focus on *gravitational potential energy*. Far from extremely massive objects, like stars, or extremely dense objects, like black holes, gravitational potential energy, PE, can be written as

$$PE = \frac{GmM}{r}$$

where the constant  $G = 6.6683 \times 10^{-11} \text{ N m}^2/\text{kg}^2$ ,  $m$  is the mass of the object whose gravitational potential energy you are measuring,  $M$  is the mass of the object generating the gravitational attraction, and  $r$  is the distance between the centers of mass of these two objects.

Near the surface of Earth, this equation simplifies to

$$PE = mgh$$

where  $g = 9.8 \text{ m/s}^2$  (32 ft/s<sup>2</sup>) is the gravitational acceleration at Earth's surface, and  $h$  is the height of the object above Earth's surface.

Potential energy can be converted into kinetic energy and vice versa. By dropping the pencil, its gravitational potential energy begins to decrease while its kinetic energy begins to increase at the *same rate*. The pencil's total energy is conserved. Conversely, if you throw a pencil up in the air, the kinetic energy you give it will immediately begin to decrease, while its potential energy increases at the same rate.

Related to the motion of an object, and hence to its kinetic energy, are the concepts of *linear momentum*, usually just called **momentum**, and **angular momentum**. Momentum,  $p$ , is described by the equation,

$$p = mv$$

where  $v$  is the velocity of the object. Both  $p$  and  $v$  are in boldface to indicate that they both represent motion in some direction or another, as well as a numeric value. Simple algebra reveals that kinetic energy and momentum are related by

$$KE = \frac{p^2}{2m}$$

Linear momentum, then, indicates how much energy is available to an object because of its motion in a straight line (linear motion).

Angular momentum,  $L$ , can be expressed mathematically as

$$L = I\omega$$

where  $I$  is the **moment of inertia** of an object, and  $\omega$  (lowercase Greek omega) is the angular speed and direction of the rotating object. Just as an object's mass indicates how hard it is to change an object's straight-line motion, the moment of inertia indicates how hard it is to change the rate at which an object rotates or revolves. The moment of inertia depends on an object's mass and shape. Kinetic energy due to angular motion can be written as

$$KE = \frac{L^2}{2I}$$

Newton's first law can also be expressed in terms of conservation of **linear momentum**:

*A body maintains its linear momentum unless acted upon by a net external force.*

Equivalently, for angular motion we can write the conservation of **angular momentum**:

*A body maintains its angular momentum unless acted upon by a net external torque.*

*Torques* are created when a force acts on an object in some direction other than toward the center of the object's angular motion, as shown in the accompanying figure.

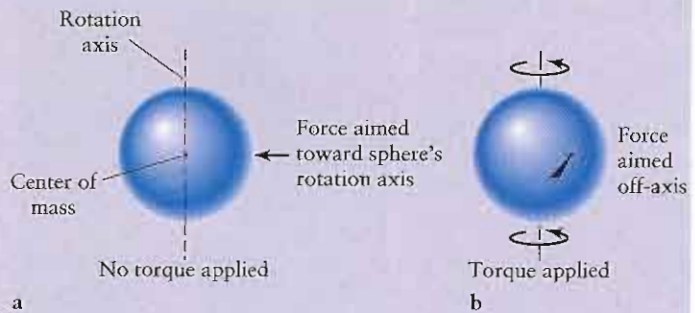
*continued on next page*

## Energy and Momentum (continued)

Earth has angular momentum and keeps spinning on its rotational axis and orbiting the Sun. Likewise, the Moon has angular momentum and keeps spinning on its rotation axis and orbiting Earth. Virtually all objects in astronomy have angular momentum, and it is probably fair to say that conservation of angular momentum is among the most important laws in the cosmos. After all, conservation of angular momentum is what keeps the planets in orbit around the Sun, the moons in orbit around the planets, and astronomical bodies rotating at relatively constant rates, as well as causing many other rotation-related effects that we will encounter throughout this book.

*Try these questions:* How does tripling the linear momentum of an object change its kinetic energy? How does halving the angular momentum of an object change its kinetic energy? How much work would you do if you pushed on a desk with a force of 100 N and moved it 20 m? How much work would you do if you pushed on a desk with a force of 500 N and moved it 0 m? What two things can you vary to change the angular momentum of an object?

(Answers appear at the end of the book.)



**Angular Momentum and Torque** (a) When a force acts through an object's rotation axis or toward its center of mass, the force does not exert a torque on the object. (b) When a force acts in some other direction, then it exerts a torque, causing the body's angular momentum to change. If the object can spin around a fixed axis, like a globe, then the rotation axis is the rod running through it. If the object is not held in place, then the rotation axis is in a line through a point called object's *center of mass*. The center of mass of any object is the point that follows a smooth, elliptical path as the object moves in response to a gravitational field. All other points in the spinning object wobble as it moves.

Force is usually expressed in pounds or newtons. For example, the force with which I am pressing down on the ground is 183 lb. But I weigh 183 lb only on Earth. I would weigh 30.5 lb on the Moon, which has less mass and so pulls me down with less gravitational force. Orbiting in the Space Shuttle, my apparent weight (measured by standing on a scale in the shuttle), would be zero, but my mass would be the same as when I am on Earth. Because I still have inertia in the shuttle, an astronaut there would have to push me with a force to get me to float across the cabin. 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.) In the same way, Newton realized that

because the Sun is exerting a force on each planet to keep it in orbit, each planet must also be exerting 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 are presented in *An Astronomer's Toolbox 2-2*. 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 *An Astronomer's Toolbox 2-2*).

It seems plausible that astronauts in the International Space Station don't 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

7

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 this skater brings her arms and outstretched leg in, she must spin faster to conserve her angular momentum. (Getty Images)

earthward, their angular momentum carries them around the planet at just the right rate to continually miss it.

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. The greater an object's angular motion or mass, or the more the mass is spread out, the greater its angular momentum. Consider, for example, a twirling ice skater. She rotates with a constant mass, practically free of outside forces. 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). According to conservation of angular momentum, as the spread of mass decreases, the rotation rate must increase. 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.

## 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 proved 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. 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 *An Astronomer's Toolbox 2-3*).

**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.*

In other words, gravitational force decreases with distance: Move twice as far away from an object and you feel only one-quarter of the force from it that you felt before. Despite its weakening, the force of gravity from each object extends throughout 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 with 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.

Newton also discovered that objects can have nonelliptical, unbound orbits. 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 have begun their existence with elliptical orbit, but some comets (small bodies of rock and ice) have received enough energy from the pull of planets or from jets of gas shooting out of them to develop parabolic or hyperbolic orbits.

Newton's ideas turned out to be applicable in an incredibly wide range of situations. The orbits of the planets and their satellites could be calculated with unprecedented precision. Using his laws, mathematicians proved that Earth's axis of rotation must precess because of the gravitational pull of the Moon and the

## AN ASTRONOMER'S TOOLBOX 2-3

## Gravitational Force

From Newton's law of gravitation, if two objects that have masses,  $m_1$  and  $m_2$ , are separated by a distance,  $r$ , then the gravitational force,  $F$ , between them is

$$F = \frac{Gm_1m_2}{r^2}$$

In this formula,  $G$  is the **universal constant of gravitation**, whose value has been determined from laboratory experiments:

$$G = 6.668 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$$

where  $N$  is the unit of force, a newton.

The equation  $F = G(m_1m_2/r^2)$  gives, for example, the force from the Sun on Earth and, equivalently, from Earth on the Sun. If  $m_1$  is the mass of Earth ( $6.0 \times 10^{24}$  kg),  $m_2$  is the mass of the Sun ( $2.0 \times 10^{30}$  kg), and  $r$  is the distance from the center of Earth to the center of the Sun ( $1.5 \times 10^{11}$  m):

$$F = 3.6 \times 10^{22} \text{ N}$$

This number can then be used in Newton's second law,  $F = ma$ , to find the acceleration of Earth due to the Sun. This yields

$$a_{\text{Earth}} = F/m_1 = 6.0 \times 10^{-3} \text{ m/s}^2$$

Newton's third law says that Earth exerts the same force on the Sun, so the Sun's acceleration due to Earth's gravitational force is

$$a_{\text{Sun}} = F/m_2 = 1.8 \times 10^{-8} \text{ m/s}^2$$

In other words, Earth pulls on the Sun, causing the Sun to move toward it. Because of the Sun's greater mass, however, the amount that the Sun accelerates Earth is more than 300,000 times greater than the amount that Earth accelerates the Sun.

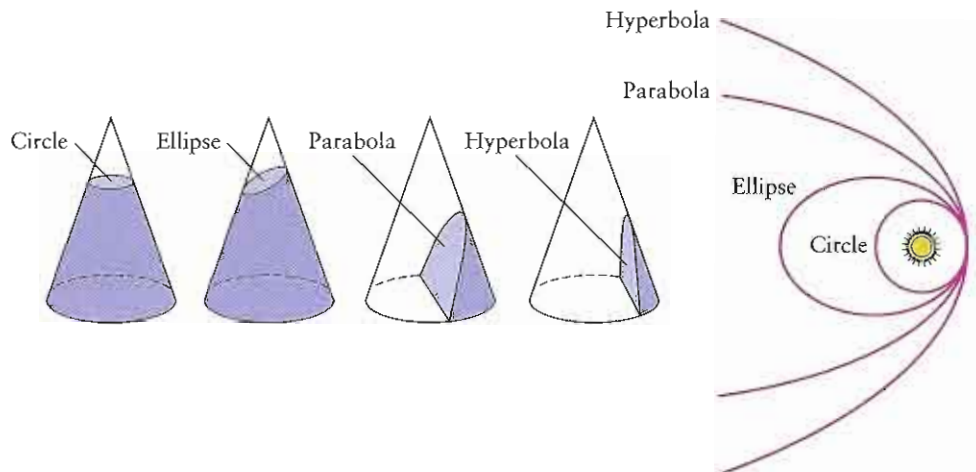
**Try these questions:** Earth's radius is  $6.4 \times 10^6$  m and 1 kg of mass is equivalent to 2.2 lb of weight on Earth. What is the force that Earth exerts on you? What is the force that you exert on Earth? What is Earth's acceleration on you? What would the Sun's force be on Earth if our planet were twice as far from the Sun as it is? How does that force compare to the force from the Sun at our present location?

(Answers appear at the end of the book.)

Sun on Earth's equatorial bulge (recall Figure 1-20). 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 their role in the discovery of the eighth planet in our solar system. The seventh planet, Uranus, had been discovered by William Herschel in 1781 during a systematic telescopic survey of the sky. Fifty years later, however, it was clear that Uranus was 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 gravitation-

al 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



**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 on ellipse, a parabola, or a hyperbola. Circular orbits are possible because a circle is just on ellipse for which both foci are at the same point.



R I V I U X 6

**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. Although dim in 1986, it nevertheless spread more than  $5^\circ$  across the sky, or 10 times the diameter of the Moon. (Harvard College Observatory/Photo Researchers, Inc.)

September 1846. A telescopic search on September 23, 1846, revealed Neptune less than  $1^\circ$  from its calculated position. Although sighted with a telescope, Neptune was really discovered with pencil and paper.

### 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.

## 2-9 Frontiers yet to be discovered

The science related to forces and orbits described in this chapter was well established by the beginning of the nineteenth century. However, questions remain. Why are the inertial mass (defined in Newton's second law) and the mass used in his law of gravitation identical? Experiments are underway at high-energy particle accelerators such as CERN, near Geneva, Switzerland, and the Fermi National Accelerator near Chicago, Illinois, to explain this. In another vein, careful observations have revealed that Newton's law of gravitation gives very slightly inaccurate predictions for the orbital path of Mercury. We will explore this further in Chapter 14.

### 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.

#### Origins of a Sun-centered Universe

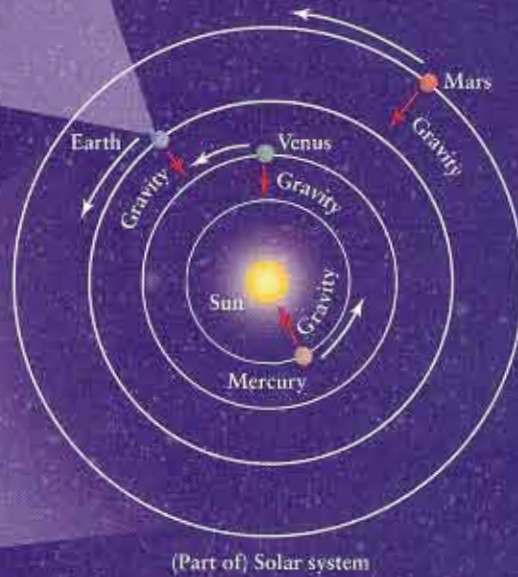
- Early Greek astronomers devised a geocentric cosmology, which placed Earth at the center of the universe.
- Copernicus's heliocentric (Sun-centered) theory simplified the general explanation of planetary motions compared to the geocentric theory.
- The heliocentric cosmology refers to motion of planets 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. It determines the length of the planet's year. Its 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.



Earth



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. Top: Space station (NASA); Couple holding hands (Paul Burns/Digital Vision/Getty Images); Center: Black hole (NASA); Bottom: Galaxy cluster (ESA, NASA, J.-P.Kneib [Caltech/Observatoire Midi-Pyrénées] and R. Ellis [Caltech])