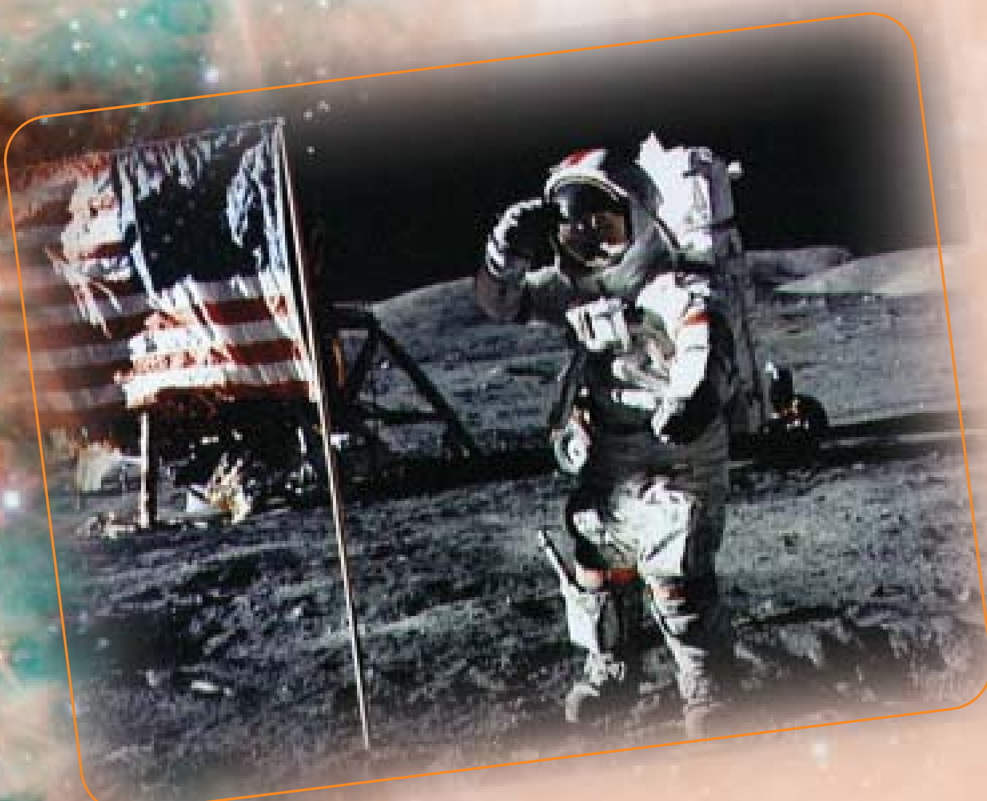
2 GRAVITATION AND THE WALTZ OF THE PLANETS

IN THIS CHAPTER YOU WILL DISCOVER

- the scientific revolution that dethroned Earth from its location at the center of the universe
- Copernicus's argument that the planets orbit the Sun
- Kepler's determination of the shapes of planetary orbits
- Galileo's first views of craters on the Moon and moons orbiting Jupiter
- how Isaac Newton used all these discoveries to formulate the basic laws of physics
- how the Sun holds the planets in their orbits



Gravity's Pull
The gravitational force of the Moon is approximately $^{1}/_{6}$th the gravitational force of the Earth. This low gravity enabled Apollo astronauts to function well in spacesuits weighing 48 kg (106 lb). Furthermore, there is very little atmosphere on the Moon. The flag in this Apollo 17 photograph has wires running through it to make it appear that it is waving in a breeze. In an experiment run on Apollo 15, astronaut Dave Scott dropped a hammer and feather simultaneously from the same height. The lack of atmosphere led to both objects striking the moon's surface simultaneously.

R I V U X G

WHAT DO YOU THINK?

1. What is the shape of the Earth's orbit around the Sun?
2. Do the planets orbit the Sun at constant speeds?
3. Do the planets all orbit the Sun at the same speed?
4. How much force does it take to keep an object moving in a straight line at a constant speed?
5. How does an object's mass differ when measured on the Earth and on the Moon?

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. Just as important, the Greeks were also among the first to leave a written record of their ideas, so that succeeding generations could develop, criticize, and test their conclusions. This concept evolved into writing physical theories quantitatively in mathematical terms so that we can test the theories by observing nature.

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: They assumed that the Sun, the Moon, the stars, and the planets revolve about the Earth. A theory of the overall structure and evolution of the universe is called a **cosmology,** so the prevailing cosmology was geocentric. Based on observations of the motions of heavenly bodies, the **geocentric cosmology** is so compelling that it held sway for nearly 2000 years. It was only in the face of more and more accurate observations of planet motions among the stars that its validity came into question.

ORIGINS OF A SUN-CENTERED UNIVERSE

The Greeks knew that the positions of the planets slowly shift against the background of "fixed" stars in the constellations. In fact, the word *planet* comes from a Greek term meaning "wanderer." The Greeks observed that planets do not move at uniform rates through the constellations. From night to night, as viewed in the northern hemisphere, they usually move slowly to the left (eastward) relative to the background stars. This eastward movement is called **direct motion.** Occasionally, however, a planet seems to stop and then back up for several weeks or months. This westward movement is called **retrograde motion.**

These planetary motions are much slower than the apparent daily movement of the entire sky caused by the Earth's rotation, and so they are superimposed on it. Therefore, the planets always rise in the east and set in the west, as the stars do. Both direct and retrograde motion are best detected by mapping the nightly position of a planet against the background stars over a long period. For example, Figure 2-1 shows the path of the planet Mars from July 2005 through February 2006.

Explaining the motions of the five planets in a geocentric (Earth-centered) universe was one of the main challenges facing the astronomers of antiquity. The effort resulted in an increasingly contrived model, especially in explaining retrograde motion. The mechanical description of a geocentric model of the universe (see Guided Discovery: Geocentric Cosmology) was complex, and, as observations improved, the model increasingly failed to fit the data. Because simplicity and accuracy are hallmarks of science, the complex geocentric model had to give way to a simpler, more elegant one. The ancient Greek astronomer Aristarchus proposed a more straightforward explanation of planetary motion, namely, that all the planets, including the Earth, revolve about the Sun.

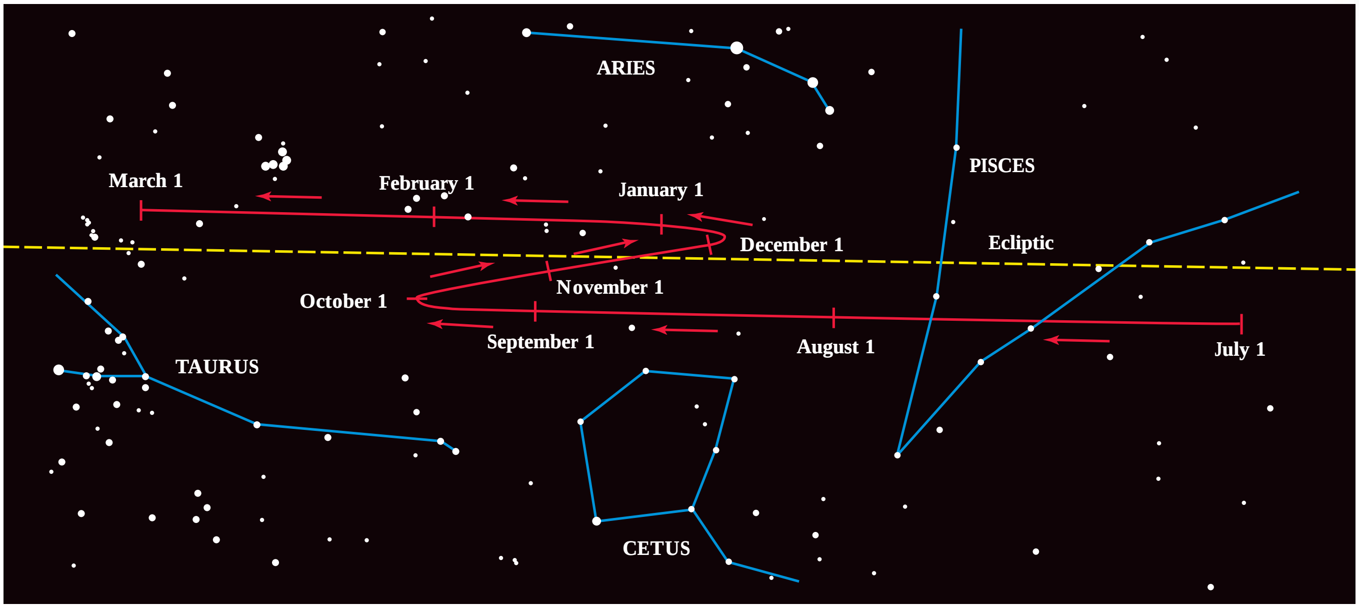
The retrograde motion of Mars in the heliocentric cosmology, for example, occurs because the Earth overtakes and passes the red planet, as shown in Figure 2-2. The occasional retrograde movement of a planet is merely the result of our changing viewpoint as we orbit the Sun—an idea that is beautifully simple compared to a geocentric system with all its complex planetary motions.

WEB LINK 2.1

Insight into Science **Keep it simple** When several competing theories describe the same concepts with the same accuracy, scientists choose the simplest one. 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 heliocentric cosmology was appealing not because it was more accurate, it wasn't, but because it made the same predictions within a simpler model than did the geocentric cosmology. *Remember Occam's razor.*

2-1 Copernicus devised the first comprehensive heliocentric cosmology

Dethroning Earth from its central role in the universe was difficult for a variety of reasons. Important among them is the fact that the Earth just doesn't seem to move! Combining this with the human desire to be at the center of everything and with geocentric religious teaching kept the belief that the Earth is at the center of everything firmly seated for more than 1300 years after Aristarchus proposed



ANIMATION 2.1

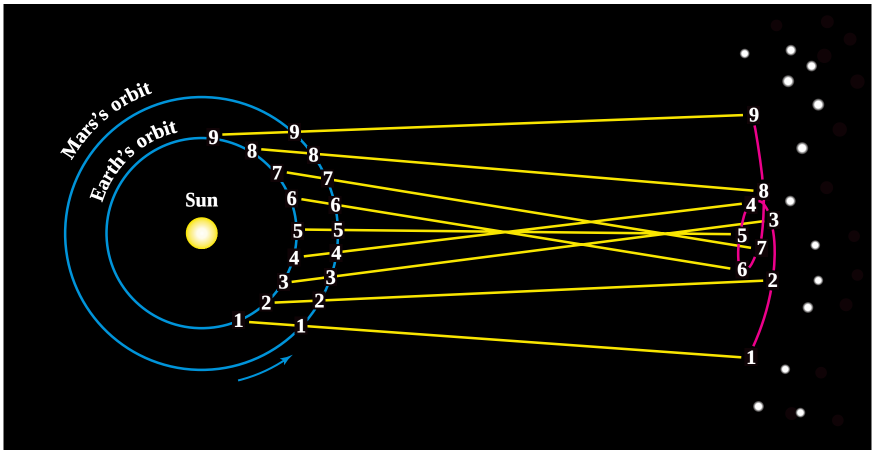
FIGURE 2-1 The Path of Mars in 2005–2006 From July 2005 through February 2006, Mars moves across the constellations of Pisces, Aries, and Taurus. From October 1 through December 12, 2005, Mars's motion will be retrograde.

the **heliocentric** (Sun-centered) **cosmology.** The person who took on the ancient authorities was the sixteenth-century Polish lawyer, physician, mathematician, economist, canon, and artist, Nicolaus Copernicus.

WEB LINK 2.2

Copernicus turned his attention to astronomy in the early 1500s. He found that by assuming that everything orbits the Sun rather than the Earth, he could determine which planets are closer to the Sun than the Earth and which are farther away. Because Mercury and Venus are always observed fairly near the Sun, Copernicus correctly concluded that their orbits must lie inside that of the Earth. The other planets visible to the naked eye—Mars, Jupiter, and Saturn—can 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 the Earth comes between the Sun and a planet. Copernicus therefore concluded that the orbits of Mars, Jupiter, and Saturn lie outside the Earth's orbit. Three more-distant planets (Uranus, Neptune, and Pluto) were discovered after the telescope was invented.

The geometrical arrangements among the Earth, another planet, and the Sun are called **configurations.** For example, when Mercury or Venus is directly between the Earth and



ANIMATION 2.2

FIGURE 2-2 A Heliocentric Explanation of Planetary Motion The Earth travels around the Sun more rapidly than does Mars. Consequently, as the 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.

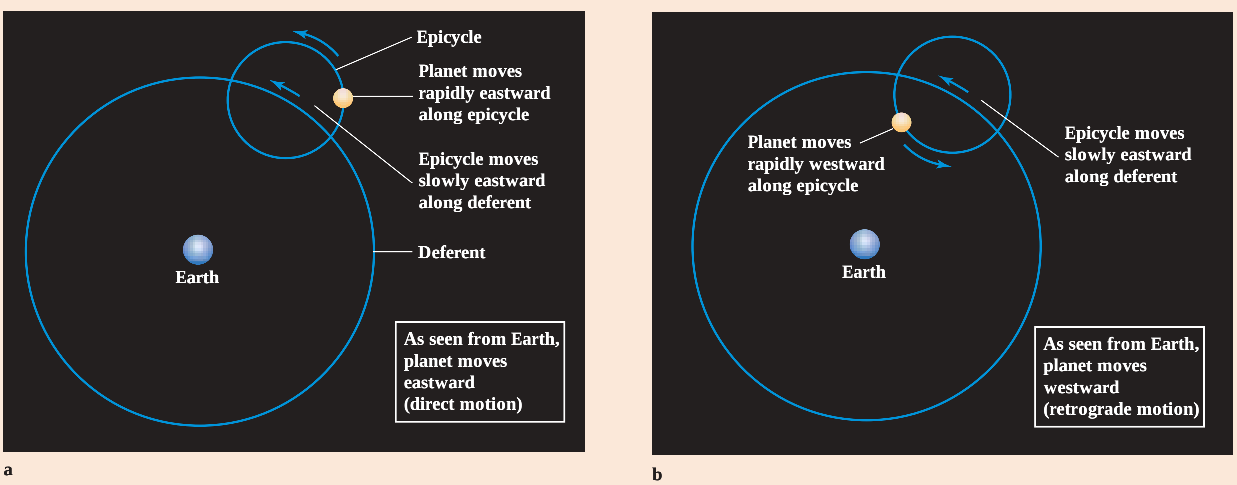
GUIDED DISCOVERY Geocentric Cosmology

The Greeks developed many theories to account for retrograde motion 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. The basic concepts are sketched in the accompanying figures. 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 the Earth. As viewed from Earth, the epicycle moves eastward along the deferent, and both circles rotate in the same direction (counterclockwise).

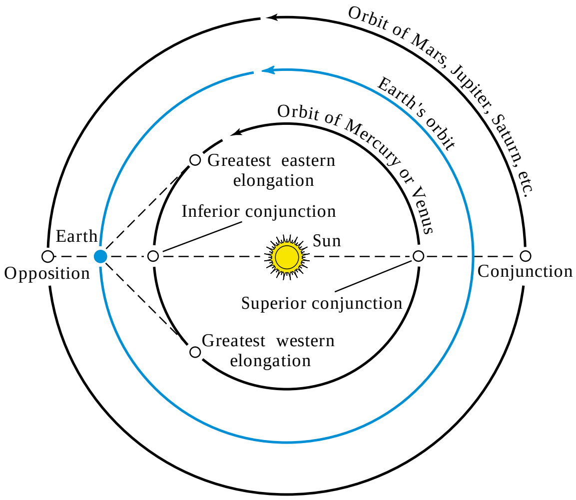
Most of the time, the motion of the planet on its epicycle adds to the eastward motion of the epicycle on the deferent. Thus, the planet is seen to be in direct (eastward) motion against the background stars throughout most of the year. However, when the planet is on the part of its epicycle nearest the 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 eastward movement among the constellations, even seeming to go backward for a few weeks or months. Using this concept of epicycles and deferents, Greek astronomers were able to explain the retrograde loops of the planets.

Using the wealth of astronomical data in the library at Alexandria, including records of planetary positions 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 the 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 complicated 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 acting on the body. However, nothing in Ptolemy's epicycle theory produced such a force.



ANIMATION 2.3 A Geocentric Explanation of Planetary Motion Each planet revolves about an epicycle, which in turn revolves about a deferent centered approximately on the 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 motion.



INTERACTIVE EXERCISE 2.1

FIGURE 2-3 **Planetary Configurations** It is useful to specify key points along a planet's orbit, as shown in this figure. These points identify specific geometric arrangements between the Earth, another planet, and the Sun.

the Sun, as in Figure 2-3, 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 the Earth, its configuration is called a **superior conjunction.**

The angle between the Sun and a planet as viewed from the 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° for Mercury and about 47° for Venus. 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 and therefore hard to see. This is especially true of Mercury, which is never more than 28° from the Sun, while Venus is often nearly halfway up the sky at sunrise or sunset and therefore quite noticeable at these times. Because they are so bright and sometimes appear to change color due to motion of the 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 whose orbits are larger than Earth's have different configurations. For example, when Mars 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 2-3. For example, when Mars is at opposition, it appears high in the sky at midnight.

It is 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 the 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. A planet's **sidereal period** is the time it takes the planet to complete one circuit around the Sun as would be measured by a fixed observer at the Sun's location watching each planet move through the background stars. The sidereal period determines the length of a year for each planet. Another useful time interval for astronomers is the **synodic period.** The synodic period is the time that elapses between two successive identical configurations as seen from the Earth. It can be from one opposition to the next, for example, or from one conjunction to the next (Figure 2-4). It tells us, for example, when to expect a planet to be closest to the Earth and, therefore, most easily studied.

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.

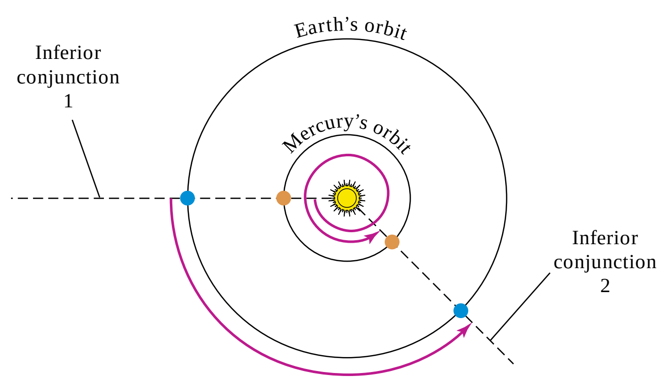


FIGURE 2-4 **Synodic Period** The time between consecutive conjunctions of the Earth and Mercury is 116 days. Typical of synodic periods for all planets, the location of the Earth is different at the beginning and end of the period. You can visualize the synodic periods of the exterior planets by putting the Earth in Mercury's place in this figure and putting one of the outer planets in the Earth's place.

TABLE 2-1 Synodic and Sidereal Periods of the Planets (in Earth Years)

	Synodic Period	Sidereal Period
Mercury	0.318 yr	0.241 yr
Venus	1.599 yr	0.616 yr
Earth	—	1.0 yr
Mars	2.136 yr	1.9 yr
Jupiter	1.092 yr	11.9 yr
Saturn	1.035 yr	29.5 yr
Uranus	1.013 yr	84.0 yr
Neptune	1.008 yr	164.8 yr
Pluto	1.005 yr	248.5 yr

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
Pluto	Unknown	39.53

Insight into Science **Take a fresh look** When the science is hard to visualize, try another perspective. For example, a planet's sidereal period of orbit is easy to understand from the perspective of the Sun but more complicated from the Earth. The synodic period of each planet, on the other hand, is easily determined from the Earth. As we will see, especially when we study Einstein's theories of relativity, each of these perspectives is called a *frame of reference.*

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. Copernicus's great insight was the simplicity of a heliocentric cosmology compared to geocentric views. However, Copernicus incorrectly assumed that the planets travel along circular paths around the Sun. As a result, his predictions were no more accurate than those of a geocentric theory!

2-2 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 12). 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. Consequently, the "new star" of 1572 could not really be a star at all, because the heavens do not change. It must instead 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.

WEB LINK 2.3

It is everyone's common experience that when you walk from one place to another, nearby objects appear to change position against the background of more distant objects. Furthermore, the closer an object is, the more you have to change the angle at which you observe it as you move. This apparent change in position of the object with the changing position of the observer is called **parallax** (Figure 2-5).

Tycho reasoned as follows: If the new star is nearby, its position should shift against the background stars over the course of a night, as shown in Figure 2-6a. His careful observations failed to disclose any parallax, and so the new star had to be far away, farther from Earth than anyone had imagined (Figure 2-6b). 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 arcminute, about as precise as is possible with the naked

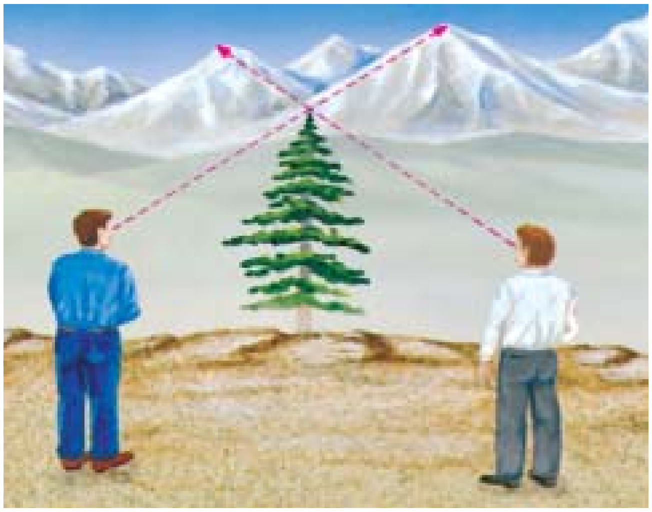


FIGURE 2-5 Parallax Nearby objects are viewed at different angles from different places. These objects also appear to be in a different place with respect to more distant objects when viewed at the same time by observers located at different positions. Both effects are called parallax, and they are used by astronomers, surveyors, and sailors to determine distances.

eye. Arcminute (arcmin) is defined in An Astronomer's Toolbox 1-1. Upon his death in 1601, most of these invaluable records were given to his gifted assistant, Johannes Kepler.

KEPLER'S AND NEWTON'S LAWS

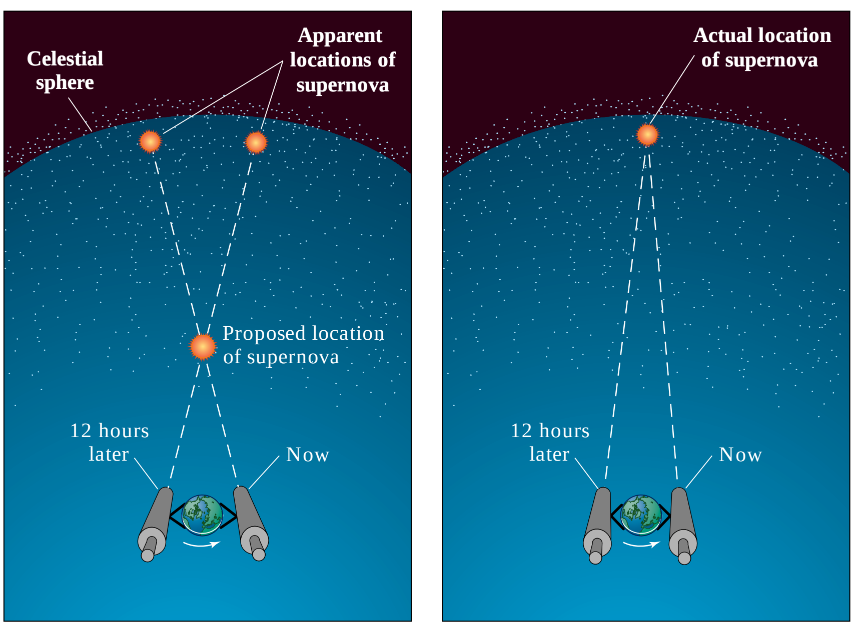
WEB LINK 2.4

Until Johannes 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 Brahe's observations of the planets' positions against the background of distant stars. Finally, he began working with a geometric form called an **ellipse.**

2-3 Kepler's laws describe orbital shapes, changing speeds, and the lengths of planetary years

An ellipse can be drawn as shown in Figure 2-7a. Each 1
thumbtack is at a **focus** (plural **foci**). The longest diameter across an ellipse, called the *major axis*, passes through both foci. Half of that distance is called the **semimajor axis,** whose length is usually designated by the letter *a*. In astronomy, the length of the semimajor axis is also the average distance between a planet and the Sun.

To Kepler's delight, the ellipse turned out to be the curve he had been searching for. 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*



a

b

FIGURE 2-6 The Parallax of a Nearby Object in Space Tycho thought that the Earth doesn't rotate and that the stars revolve around it. From our modern perspective, the changing position of the supernova would be due to the Earth's rotation as shown in this figure. (a) Tycho Brahe argued that if an object is near the 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 the Earth.

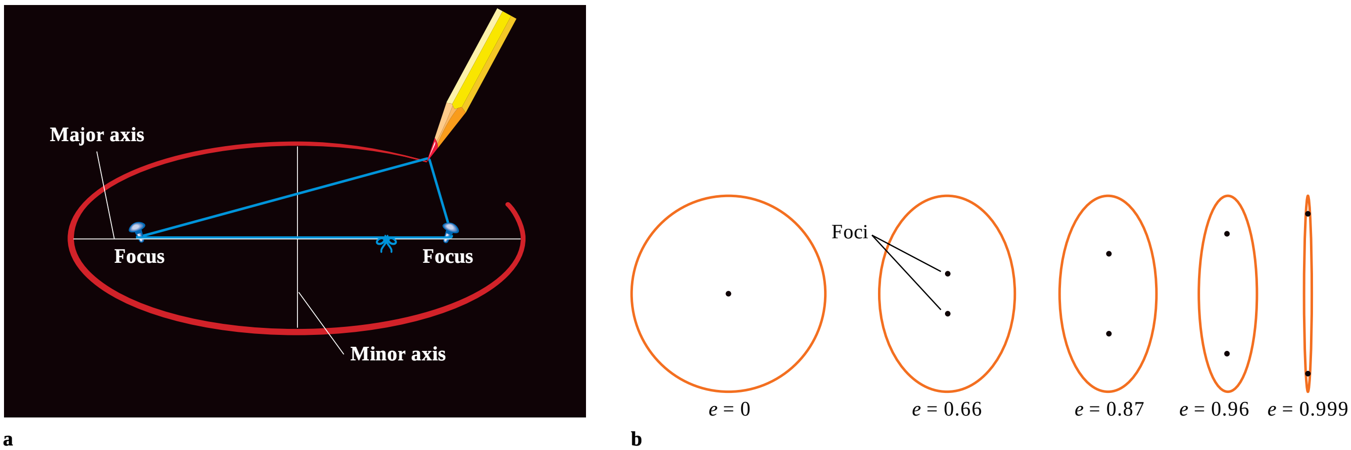


FIGURE 2-7 Ellipse (a) The construction of an ellipse: An ellipse can be drawn with a pencil, a loop of string, and two thumbtacks, as shown in this figure. If the string is kept taut, the pencil traces out an ellipse. The two thumbtacks are located at the two foci of the ellipse. (b) A series of ellipses with different eccentricities, *e*. Eccentricities range between 0 (circle) to just under 1.0 (almost a straight line).

Astronomy. This important discovery is now considered the first of **Kepler's laws:**

The orbit of a planet about the Sun is an ellipse with the Sun at one focus.

Ellipses have two extremes. The roundest ellipse 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 2-7b shows a sequence of ellipses and their associated eccentricities. Observations have since revealed that there is no object at the second focus of each elliptical planetary orbit.

2 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, a point called **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 2-8. 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 2-8). 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 2-8 are equal in area. Kepler's second law, also called the **law of equal areas,** can be stated thus:

A line joining a planet and the Sun sweeps out equal areas in equal intervals of time.

The physical content of Kepler's second law is that each planet's speed decreases as it moves from perihelion to aphe-

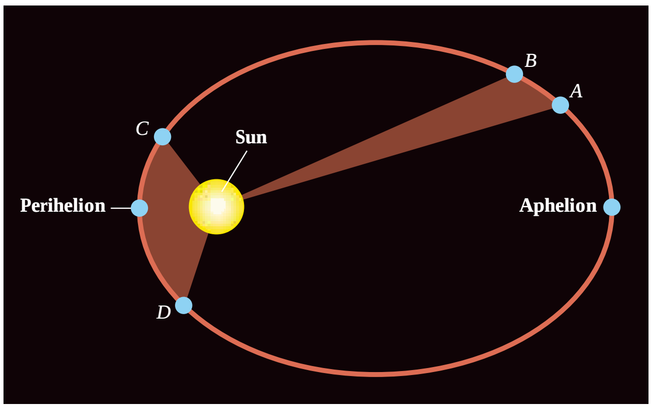


FIGURE 2-8 Kepler's First and Second Laws According to Kepler's first law, every planet travels around the Sun along an elliptical orbit with the Sun at one focus. According to his second law, the line joining the planet and the Sun sweeps out equal areas in equal intervals of time. *Note:* This drawing 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.

lion. The speed then increases as the planet moves from aphelion toward perihelion.

ANIMATION 2.4

Kepler was also able to relate a planet's year to its distance from the Sun. This discovery, published in 1619, stands out because of its impact on future developments in astronomy. Now called *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:

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 (as we discussed in An Astronomer's Toolbox I-2). Now we can write Kepler's third law as

$$P^2 = a^3$$

In other words, a planet closer to the Sun has a shorter
3 year than does a planet farther from the Sun. Combining this with the 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 below, he discovered that there is contribution to the period from the mass of the planet. However, this correction is vanishingly small for all the planets in the solar system, which is why the above equation, as shown in Table 2-3, gives such good results for the planets' orbits.

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 laws work are unknown. The explanation for Kepler's laws came decades after Kepler deduced them, in 1665, when Newton applied his mathematical expression for gravitation, the force that holds the planets in their orbits.

2-4 Galileo's discoveries strongly supported a heliocentric cosmology

While Kepler was making rapid progress in central Europe, an Italian physicist was making equally 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 sunspots on the Sun. He also discovered that Venus exhibits phases.

WEB LINK 2.5

After only a few months of observation, Galileo noticed that the apparent size of Venus as seen through his telescope was related to the planet's phase. Venus appears smallest at gibbous phase and largest at crescent phase. A geocentric cosmology could not explain why, but a heliocentric cosmology does. Galileo's observations therefore supported the conclusion that Venus orbits the Sun, not the Earth (Figure 2-9).

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

ANIMATION 2.5

TABLE 2-3 A Demonstration of Kepler's Third Law

	Sidereal period P (yr)	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	7,058		7,067
Neptune	164.79	30.06	27,160		27,160
Pluto	248.54	39.53	61,770		61,770

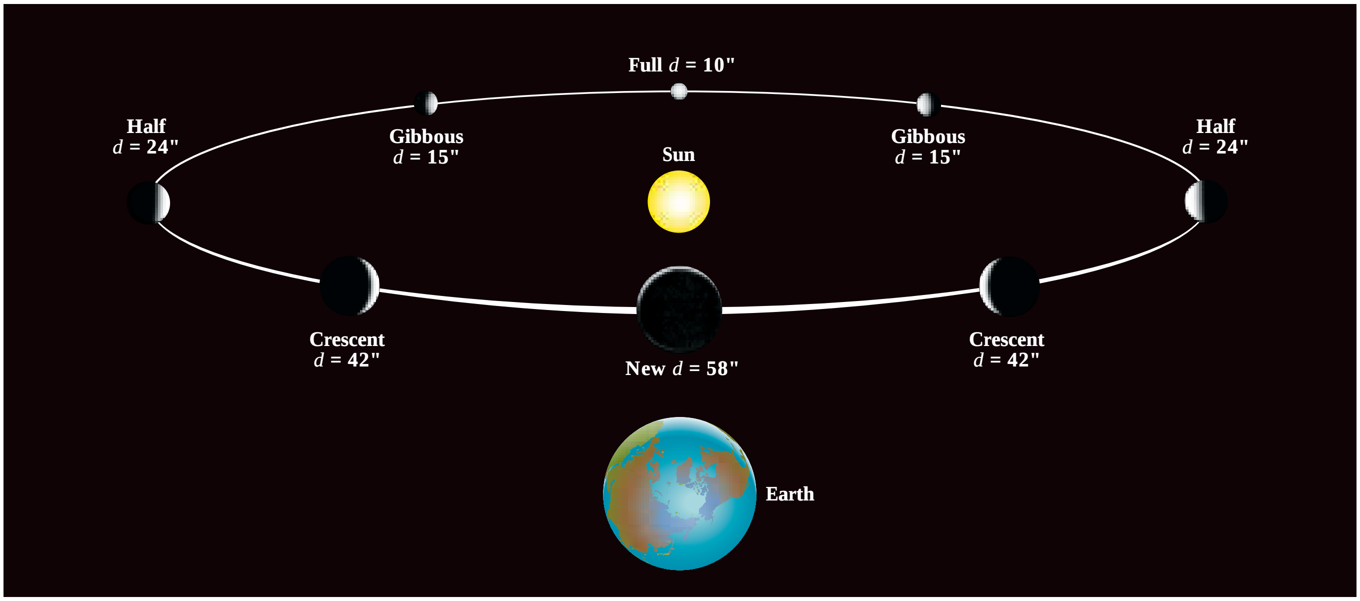


FIGURE 2-9 The Changing Appearance of Venus This figure shows how the appearance (phase) of Venus changes as it moves along its orbit. The number below each view is the angular diameter (d) of the planet as seen from Earth, in arcseconds. Note that the phases correlate with the planet's angular size and its angular distance from the Sun, both as seen from Earth. These observations clearly support the idea that Venus orbits the Sun.

Galileo concluded that the moons are orbiting Jupiter because they move across from one side of the planet to the other. Confirming observations were made in 1620 (Figure 2-10). These observations all provided further proof that the Earth is not at the center of the universe. Like the Earth in orbit around the Sun, Jupiter's four moons obey Kepler's third law: The square of a moon's orbital period about 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 latter years under house arrest "for vehement suspicion of heresy."

A major stumbling block prevented seventeenth-century thinkers from accepting Kepler's laws and Galileo's conclusions about the heliocentric cosmology. At that time, the relationships between matter, motion, and forces were not understood. People did not know about the gravitational force of the Sun, which keeps the planets in orbit. They did not know how planets, since they had started in orbit around the Sun, could keep moving. Once anything on Earth is put in motion, it quickly comes to rest. Why didn't the planets orbiting the Sun stop, too?

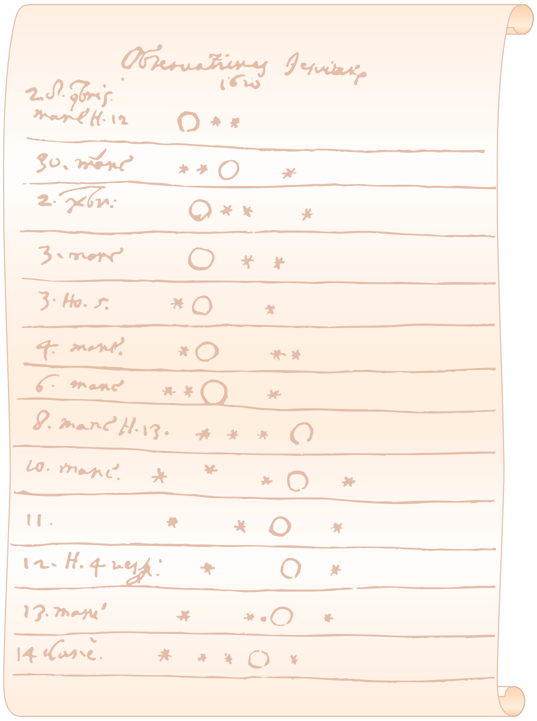
All those mysteries were soon explained by the brilliant and eccentric scientist Isaac Newton, who was born on Christmas Day in 1642, less than a year after Galileo died. In the decades that followed, Newton revolutionized science more profoundly than any person before him, and in doing so, he found physical and mathematical proofs of the heliocentric cosmology.

2-5 Newton formulated three laws that describe fundamental properties of physical reality

WEB LINK 2.6

Until the mid-seventeenth century, virtually all mathematical astronomy used the same approach. Astronomers from Ptolemy to Kepler worked *empirically,* that is, directly from data and observations. They adjusted their ideas and calculations until they finally came out with the right answers.

Isaac Newton introduced a new approach. He made just three assumptions, now called **Newton's laws of motion,** which he applied to all forces and bodies. He also found a formula for the force of **gravity,** the attraction between all objects due to their masses. Newton then showed that Kepler's three laws mathematically and, hence, physically, fol-



a

b

RIVUXG

FIGURE 2-10 Jupiter and Its Largest Moons (a) 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 the Earth. This figure shows observations made by Jesuits in 1620. (b) This 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. (b: Courtesy of C. Holmes)

low from these laws. Using his formula, Newton accurately described the observed orbits of the Moon, comets, and other objects in the solar system. His laws also apply to the motions of all bodies on the Earth.

Newton's first law, the **law of inertia,** states that

4 *A body remains at rest or moves in a straight line at a constant speed unless acted upon by a net outside force.*

At first, this law might seem to conflict with your everyday experience. For example, if you shove a chair, it does not continue at a constant speed forever but rather it comes to rest after sliding only a short distance. From Newton's viewpoint, however, a "net outside 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 **force** changes the motion of an object.

Newton's first law tells us that there must be an outside force acting on the planets. If there were no force acting on them, they would move away from the Sun along straight-line paths at constant speeds. In other words, they would leave their curved orbits. 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 assumption describes how a force changes the motion of an object. To appreciate the concepts of force and motion better, we must first understand the quantities that describe motion: speed, velocity, and acceleration.

Imagine an object in space. Push on the object 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 the 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 types of acceleration.

Suppose an object revolved about the Sun in a perfectly circular orbit. This body would have acceleration that involved only a change of direction. As this object moved along its orbit, its speed would remain constant, but its direction of motion would be continuously changing. Therefore, it would still be continuously accelerating.

Newton's second law says that the acceleration of an object is proportional to the force acting on it. In other words, the harder you push on an object, the greater the resulting acceleration. Newton's law also says that a greater mass pushed or pulled by a force accelerates more slowly than does an object of lesser mass pushed or pulled by the same force. That is why by pushing a child's wagon, you can accelerate it faster than you can accelerate a car by pushing

MOVIE MISCONCEPTIONS

Planet of the Apes (Twentieth Century Fox, 2001)
(The Kobal Collection)

Director Tim Burton reinvents Pierre Boulle's classic novel in the newest *Planet of the Apes* movie. Set in the year 2029, the film opens on a space station orbiting Saturn. The station is shown to not be rotating. We know this because the actors are standing and walking on the disk-shaped floors, occasionally looking out windows along the edge of the station. (If the station were rotating, the actors would be standing facing inward on the outer, curved edge of the structure, as was depicted in the Stanley Kubrick movie *2001: A Space Odyssey*). The actors wear normal shoes, and things lying on tables remain in place even when the station undergoes slight jostling.

A short time into the movie the hero enters a vehicle, puts on a helmet that rests on his jacket, and leaves the space station. It is worth noting that space helmets are designed to be part of airtight spacesuits that protect astronauts in case their spacecraft loses air pressure.

Describe the two scientific errors in *Planet of the Apes* as described in the paragraphs above.

(Answers appear at the end of the book.)

on it. 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 amount
5 of material in the object, which we measure in kilograms. For example, the mass of the Sun is 2×10^{30} kg, the mass of a hydrogen atom is 1.7×10^{-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 that of weight. **Weight** is the force with which an object is pulled down while on the ground (due to gravity's attraction) or, equivalently, feels inside an accelerating rocket. Force is usually expressed in pounds or newtons. For example, the force with which I am pressing down on the ground is 183 pounds.

But I weigh 183 pounds only on the Earth. I would weigh less on the Moon. 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. An astronaut in the shuttle would still have to push me with a force to get me to move. 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 famous *law of action and reaction:*

Whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body.

For example, I weigh 183 pounds, and so I press down on the floor with a force of 183 pounds. Newton's third law says that the floor is also pushing up against me with an equal force of 183 pounds. (If it was less, I would fall through the floor, and if it was 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.

The Sun is pulling the planets, so why don't they fall onto it? **Conservation of angular momentum,** a fundamental consequence of Newton's second law of motion, provides the answer. Angular momentum is a measure of how much energy is stored in an object due to its rotation and revolution (presented in An Astronomer's Toolbox 2-1). As the orbiting planets fall Sunward, their angular momentum provides them with motion perpendicular to that infall, meaning that planets continually fall toward the Sun, but they continually miss it. Because their angular momentum is conserved, planets neither spiral into the Sun or away from it. Angular momentum remains constant unless acted on by an outside torque.

Angular momentum depends on three things: how fast the body rotates or revolves, how much mass it has, and how spread out that mass is. The greater a body's angular motion or mass, or the more the mass is spread out, the greater its angular momentum. Consider, for example, a twirling ice

AN ASTRONOMER'S TOOLBOX 2-1

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, in an object as:

$$KE = {}^1/_2\, mv^2$$

where m is the object's mass (total number of particles) and v is its velocity. 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 put the object in motion.

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 times 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 newtons (a unit of force) and thereby move an object 10 meters in that direction, then I have done 50 N × 10 m = 500 joules of work. (I have used the relationship that 1 newton × 1 meter = 1 joule.)

The second type of energy is called **potential energy.** It represents how much energy is stored in 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 the 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 can be written as:

$$PE = GmM/r$$

where $G = 6.668 \times 10^{-11}$ N m^2/kg^2, m is the mass of the object whose gravitational potential energy you are measuring, M is the mass of the object creating the gravitational potential energy, and r is the distance between the centers of masses of the object feeling the gravitational potential energy and the object creating that energy.

Near the surface of the Earth, this equation simplifies to:

$$PE = mgh$$

where $g = 9.8$ m/s^2 is the gravitational acceleration at the Earth's surface, and h is the height of the object above the Earth's surface.

Potential energy can be converted into kinetic energy and vice versa. By dropping the pencil, its gravitational potential energy begins decreasing while its kinetic energy begins increasing *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 decreasing, 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 having some numerical value. Simple algebra reveals that kinetic energy and momentum are related by:

$$KE = p^2/2m$$

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

Angular momentum, L, can be expressed mathematically as:

$$L = I\omega$$

where I is the moment of inertia of an object and ω gives the speed and direction in which it is revolving or rotating. Just as the 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 stored in angular motion can be written:

$$KE = L^2/2I$$

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:

(*continued on the following page*)

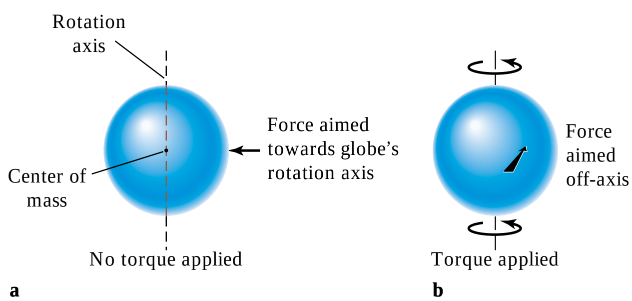
AN ASTRONOMER'S TOOLBOX 2-1 (continued)

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 figure. The Earth has angular momentum and keeps spinning on its rotational axis and orbiting around the Sun. Likewise, the Moon has angular momentum and keeps spinning on its rotation axis and orbiting the Earth. Virtually all objects in astronomy have angular momentum, and I think it's fair to say that conservation of angular momentum is among the most important laws in the cosmos. After all, it is what keeps the planets in orbit around the Sun, the moons in orbit around the planets, the astronomical bodies rotating at relatively constant rates, and 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, then 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 the object's center of mass. The center of mass of any object is the point that follows an elliptical, parabolic, or hyperbolic path in a gravitational field. All other points in the spinning object wobble as it moves.

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 in closer to her body. According to the 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, like stars, contract.

We have now reconstructed the central relationships between matter and motion. Scientific belief in 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.

2-6 Newton's description of gravity accounts for Kepler's laws

Isaac Newton did not invent the idea of gravity. An educated seventeenth-century person would understand that some force pulls things down to the ground. It was Newton, however, who gave us a precise description of the action of gravity, or *gravitation*, as it is more properly called. Using his first law, Newton proved mathematically that the force acting on each of the planets is directed toward the Sun. This discovery led him to suspect 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 that is always aimed straight at the Sun.

Newton succeeded in formulating a mathematical model describing the behavior of the gravitational force that keeps the planets in their orbits (presented in An Astronomer's Toolbox 2-2). Newton's **universal law of gravitation** states:

Two bodies 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 a body and you feel only one-quarter of the force from it that you felt before.

Using his law of gravity, 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,

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.

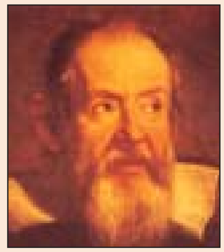

(E. Lessing/Art Resource)

Nicolaus Copernicus (1473–1543) Copernicus was born in Torun, Poland, the youngest of four children. 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 published his work in 1543 under the title *De revolutionibus orbium coelestium*. Copernicus became ill and died just after receiving the first copy.


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

Tycho Brahe (1546–1601) and **Johannes Kepler (1571–1630)** Tycho, depicted within a 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. He rejected Copernicus's heliocentric theory and the Ptolemaic geocentric system and devised a halfway theory called the "Tychonic system." According to Tycho's theory, the 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 Two New Sciences*, published in 1632.


(National Portrait Gallery, London)

Isaac Newton (1642–1727) Although he delighted in constructing mechanical devices—sundials, model windmills, a water clock, and a mechanical carriage—Newton showed no exceptional academic ability at Cambridge University, where he received a bachelor's degree in 1665. 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.

are related by $P^2 = a^3$, Newton demonstrated mathematically that this equation (corrected with a tiny contribution due to the mass of the planet) follows from his law of gravitation.

Newton's version of Kepler's third law can be easily recast to predict the orbits of any objects under the influence of a gravitational attraction. Indeed, all three of Kepler's laws apply to all orbiting bodies. This includes moons orbiting planets, artificial satellites orbiting the Earth, and even two stars revolving about each other. Throughout this book, we will see that Kepler's three laws have a wide range of practical applications.

Newton also discovered that some objects have nonelliptical orbits around the Sun. His equations led him to conclude that the orbits of some objects are **parabolas** and

AN ASTRONOMER'S TOOLBOX 2-2

Gravitational Force

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

$$F = G(m_1 m_2/r^2)$$

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 $F = G(m_1 m_2/r^2)$ gives, for example, the force from the Sun on the Earth and, equivalently, from the Earth on the Sun. If m_1 is the mass of the Earth (6.0×10^{24} kg), m_2 is the mass of the Sun (2.0×10^{30} kg), and r is the distance from the Earth to the Sun (1.5×10^{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 the 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 the Earth exerts the same force on the Sun, so the Sun's acceleration due to the Earth's gravitational force is

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

In other words, the 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 the Earth is more than 300,000 times the amount that the Earth accelerates the Sun.

Try these questions: The Earth's radius is 6.4×10^6 m and 1 kg = 2.2 lb. What is the force that the Earth exerts on you? What is the force that you exert on the Earth? What is the Earth's acceleration on you? What would the Sun's force be on the 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?

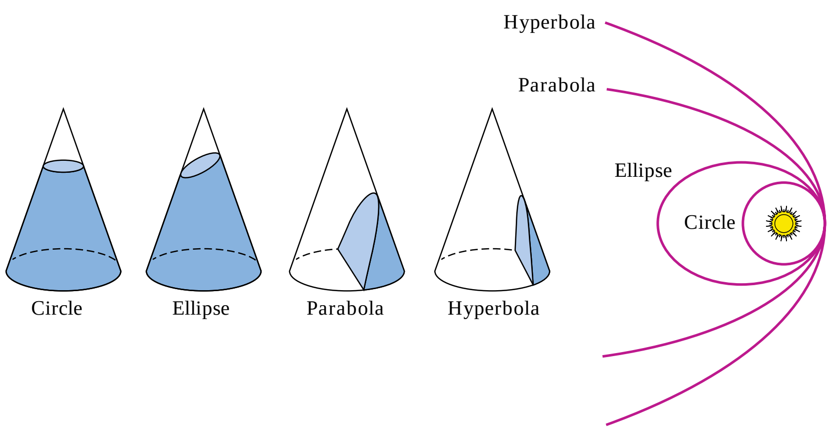
(Answers appear at the end of the book.)

hyperbolas (Figure 2-11). For example, comets hurtling toward the Sun from the depths of space often follow 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 now be calculated with unprecedented precision. Using Newton's laws, mathematicians proved that the Earth's axis of rotation must precess because of the gravitational pull of the Moon and the Sun on the Earth's equatorial bulge (recall Figure 1-17).

ANIMATION 2.6

In addition, Newton's laws and mathematical techniques were used to predict new phenomena. Newton's friend, Edmund Halley, was intrigued by historical records of a comet that was sighted about every



INTERACTIVE EXERCISE 2.2

FIGURE 2-11 Conic Sections A conic section is any one of a family of curves obtained by slicing a cone with a plane, as shown in this figure. The orbit of one body about 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.

R I V U X G

FIGURE 2-12 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, shown here, in 1986. The comet will pass close to the Sun again in 2061. While dim in 1986, it nevertheless spread more than 5° across the sky, or 10 times the diameter of the Moon. (Science Photo Library)

76 years. Using 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 2-12).

Perhaps the most dramatic confirmation of Newton's ideas was their role in the discovery of the eighth planet in our solar system. The seventh planet, Uranus, had been discovered accidentally by William Herschel in 1781 during a 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 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, revealed Neptune less than 1° from its calculated position. Although sighted with a telescope, Neptune was really discovered with pencil and paper (Figure 2-13).

Insight into Science **Quantify predictions** Mathematics provides a language that enables science to make quantitative predictions that can be checked by anyone. For example, we have seen in this chapter 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.

Over the years, Newton's ideas were successfully used to predict and explain motion here on Earth and throughout the universe. Even today, as we send astronauts into Earth orbit and send probes to the outer planets, Newton's equations are used to calculate the orbits and trajectories of the spacecraft.

It is a testament to Newton's genius that his three laws were precisely the basic ideas needed to understand the motions of the planets. Newton brought a new dimension of elegance and sophistication to our understanding of the workings of the universe.

a **b**

R I V U X G

FIGURE 2-13 Uranus and Neptune The discovery of Neptune was a major triumph for Newton's laws. In an effort to explain why Uranus (shown on the left, with two of its moons) deviated from its predicted orbit, astronomers predicted the existence of Neptune (shown on the right, with one of its moons indicated by an arrow). Uranus and Neptune are nearly the same size; both have diameters about 4 times that of Earth. (a: John Chumack/Photo Researchers; b: NASA)

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 remained. Careful observation revealed that Newton's law of gravitation gave very slightly inaccurate predictions for the orbital path of Mercury. We will see in Chapter 13 that this problem was resolved by Albert Einstein. Nevertheless, one fundamental question from this chapter's material remains to be answered: What is "mass"? Many physicists studying the building blocks of matter (such as the elementary particles protons, neutrons, and electrons) believe that mass comes from the presence of a particle permeating the universe called the Higgs boson. When elementary particles interact with it, they gain the property we call mass. Searches for Higgs bosons are underway at high-energy particle accelerators such as CERN, near Geneva, Switzerland, and the Fermi National Accelerator in Illinois. If these experiments are successful, then we may know the origin of mass by the end of this decade.

For Further Reading

WHAT DID YOU KNOW?

1 *What is the shape of the Earth's orbit around the Sun?* All planets have elliptical orbits around the Sun.

2 *Do the planets orbit the Sun at constant speeds?* No. The closer a planet is to the Sun in its orbit, the faster it is moving. It moves fastest at perihelion and slowest at aphelion.

3 *Do the planets all 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, the most distant planet moves slowest.

4 *How much force does it take to keep an object moving in a straight line at a constant speed?* Unless an object is subject to an outside force, like friction, it takes no force at all to keep it moving in a straight line at a constant speed.

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 remains constant whether on the Earth or on the Moon. Its weight, however, is less on the Moon.

KEY WORDS

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KEY IDEAS

• The ancient Greeks laid the groundwork for progress in science. Early Greek astronomers devised a geocentric cosmology, which placed the Earth at the center of the universe.

Origins of a Sun-Centered Universe

• Copernicus's heliocentric (Sun-centered) theory simplified the general explanation of planetary motions compared to the geocentric theory.

• In a heliocentric cosmology, the Earth is but one of several planets that 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 circles. 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, that 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 universal law of gravitation can be used to deduce Kepler's laws and to describe planetary motions with extreme accuracy.

• The mass of an object is a measure of the amount of matter in the object; its weight is a measure of the force with which the gravity of some other object pulls on the object's mass.

• In general, the path of one astronomical object about another, such as that of a comet about the Sun, is an ellipse, a parabola, or a hyperbola.

REVIEW QUESTIONS

1 How did Copernicus explain the retrograde motions of the planets?

2 Which planets can never be seen at opposition? Which planets can never be seen at inferior conjunction?

3 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.

4 What are the synodic and sidereal periods of a planet?

5 What are Kepler's three laws? Why are they important?

6 In what ways did the astronomical observations of Galileo support a heliocentric cosmology?

7 How did Newton's approach to understanding planetary motions differ from that of his predecessors?

8 What is the difference between mass and weight?

9 Why was the discovery of Neptune a major confirmation of Newton's universal law of gravitation?

10 Why does an astronaut have to exert a force on a weightless object to move it?

ADVANCED QUESTIONS

The answers to all computational problems, which are preceded by an asterisk (*), appear at the end of the book.

11 Is it possible for an object in the solar system to have a synodic period of exactly one year? Explain your answer.

12 Explain qualitatively (in words) the systematic decrease in the synodic periods of the planets from Mars outward, as shown in Table 2-1.

***13** A line joining the sun and an asteroid was found to sweep out 5.2 square astronomical units of space in 1994. How much area was swept out in 1995? in five years?

***14** A comet moves in a highly elongated orbit about the Sun with a period of 1000 years. What is the length of the semimajor axis of the comet's orbit? What is the farthest the comet can get from the Sun?

***15** The orbit of a spacecraft about the Sun has a perihelion distance of 0.5 AU and an aphelion distance of 3.5 AU. What is the spacecraft's orbital period?

16 Look up orbital data for the largest moons of Jupiter on the Internet, in the current issue of a reference from the U.S. Naval Observatory, such as the *Astronomical Almanac* or *Astronomical Phenomena,* or in such magazines as *Sky & Telescope* and *Astronomy.* Demonstrate that these orbits obey Kepler's third law.

17 Make diagrams of Jupiter's phases as seen from Earth and as seen from Saturn.

18 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?

DISCUSSION QUESTIONS

19 Which planet would you expect to exhibit the greatest variation in apparent brightness as seen from earth? Explain your answer.

20 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.

WHAT IF ...

***21** The Earth were 2 AU from the Sun? What would the length of the year be? Assuming such physical properties as rotation rate were as they are today, what else would be different here? What if the Earth was 1/2 AU from the Sun?

***22** The Earth was moved to a distance of 10 AU from the Sun? How much stronger or weaker would the Sun's gravitational pull be on Earth?

***23** The Earth had twice its present mass? Assume that all other properties of the Earth and its orbit remain the same. What would be the acceleration of the New Earth due to the Sun compared to the present acceleration of the Earth from the Sun? *Hint:* Try combining $F = m_1a$ and the force equation in An Astronomer's Toolbox 2-2, where m_1 is the mass of the Earth in both equations. Since the acceleration determines the period of the planet's orbit, how would the year on the more massive Earth compare to a year today?

24 The Sun suddenly disappeared? What would the Earth's path in space be in response to such an event? Describe how the Earth would change as a result and how humans might survive on a sunless planet.

WEB/CD-ROM QUESTIONS

25 Search the Web for information about Galileo. What were his contributions to physics? Which of Galileo's new ideas were later used by Newton to construct his laws of motion? What incorrect beliefs about astronomy did Galileo hold?

26 Search the Web for information about Kepler. Before he realized that the planets move on elliptical paths, what other models of planetary motion did he consider? What was Kepler's idea of the "music of the spheres"?

27 Search the Web for information about Newton. What were some of the contributions that he made to physics other than developing his laws of motion? What contributions did he make to mathematics?

ANIMATION 2.1

28 **Monitoring the Retrograde Motion of Mars** Access and view the animation "The Path of Mars in 2004–2005" in Chapter 2 of the *Discovering the Universe* Web site or CD-ROM. (a) Through which two constellations does Mars move? (b) On approximately what date does Mars stop its direct (west to east) motion and begin its retrograde motion? *Hint:* Use the "Stop" and "Start" functions on your animation controls. (c) Over how many days does Mars move in the retrograde direction?

OBSERVING PROJECTS

STARRY NIGHT

29 It is quite probable that within a few weeks of your reading this chapter one of the planets will be in opposition or at greatest eastern elongation, making it readily visible in the evening sky. Using the *Starry Night Backyard*™ computer program, the Internet, or consulting a reference book, such as the current issue of the *Astronomical Almanac* or the pamphlet *Astronomical Phenomena* (both published by the U.S. government), select a planet that is at or near such a configuration. To use *Starry Night Backyard*™, set the time for this evening, right click on the screen and make sure "show planets" is checked. Press the Labels button at the top and make sure "planets/Sun" is checked. Then grab the screen with the mouse and search the sky for planets. If none are up, change the date by, say, three days and search again. Repeat until you have found visible planets up at night. Plan to make your observations at that time. At opposition, would you predict that planets move rapidly or slowly from night to night against the background stars? Verify your predictions by observing the planet once a week for a month, recording your observations on a star chart. How can you determine whether the change in position that you observe represents rapid or slow motion across the celestial sphere?

30 If Jupiter is visible in the evening sky, observe it with a small telescope on five consecutive clear nights. Record the position of the four Galilean satellites by making nightly drawings, just as the Jesuit priests did in 1620 (see Figure 2-10). From your drawings, can you tell which moon orbits closest to Jupiter and which orbits farthest? Are there nights when you saw fewer than four of the Galilean moons? What happened to the other moons on those nights?

STARRY NIGHT

31 Use the *Starry Night Backyard*™ software to observe the moons of Jupiter. Set for Atlas mode (*Go:Atlas*). Center and lock on Jupiter (*Edit:Find:Jupiter*) and set the angular size of the sky you are examining to 30′ using the size button on the upper right of your screen. Lock on Jupiter (right click on Jupiter, click on Centre/Lock). (a) Note the positions of the moons. Step forward in increments of six hours and draw the positions of the moons at each timestep. (b) From your drawings, can you tell which moon orbits closest to Jupiter and which orbits farthest away? Explain your reasoning. (c) Determine the periods of orbits of these moons. (d) Are there timesteps when you see fewer than four Galilean moons? What happened to the other moons at those times?

32 If Venus is visible in the evening sky, observe the planet with a small telescope once a week for a month. On each night, make a drawing of the phase that you see. Can you determine from your drawings if the planet is nearer or farther from the Earth than the Sun is? Do your drawings show any changes in the phase from one week to the next? If so, can you deduce if Venus is coming toward us or moving away from us?

33 Use your *Starry Night Backyard*™ software to observe the phases of Venus. Set for Atlas mode (*Go:Atlas*). Center and lock on Venus (*Edit:Find: Venus*). Set the angular size of the sky to 7′. (a) Draw the current shape (phase) of Venus. Adjust the timestep to 30 days, make a single timestep, and again draw Venus, to scale. Make a total of 20 timesteps and drawings. (b) From your drawings, determine when the planet is nearer or farther from the Earth than the Sun is. (c) Deduce from your drawings when Venus is coming toward us or is moving away from us. (d) Explain why Venus goes through this particular cycle of phases.

34 Perform observing project 32 using Mars instead of Venus. If you have done project 32, compare your results for the two planets. Why are the cycles of phases as seen from Earth different for the two planets?