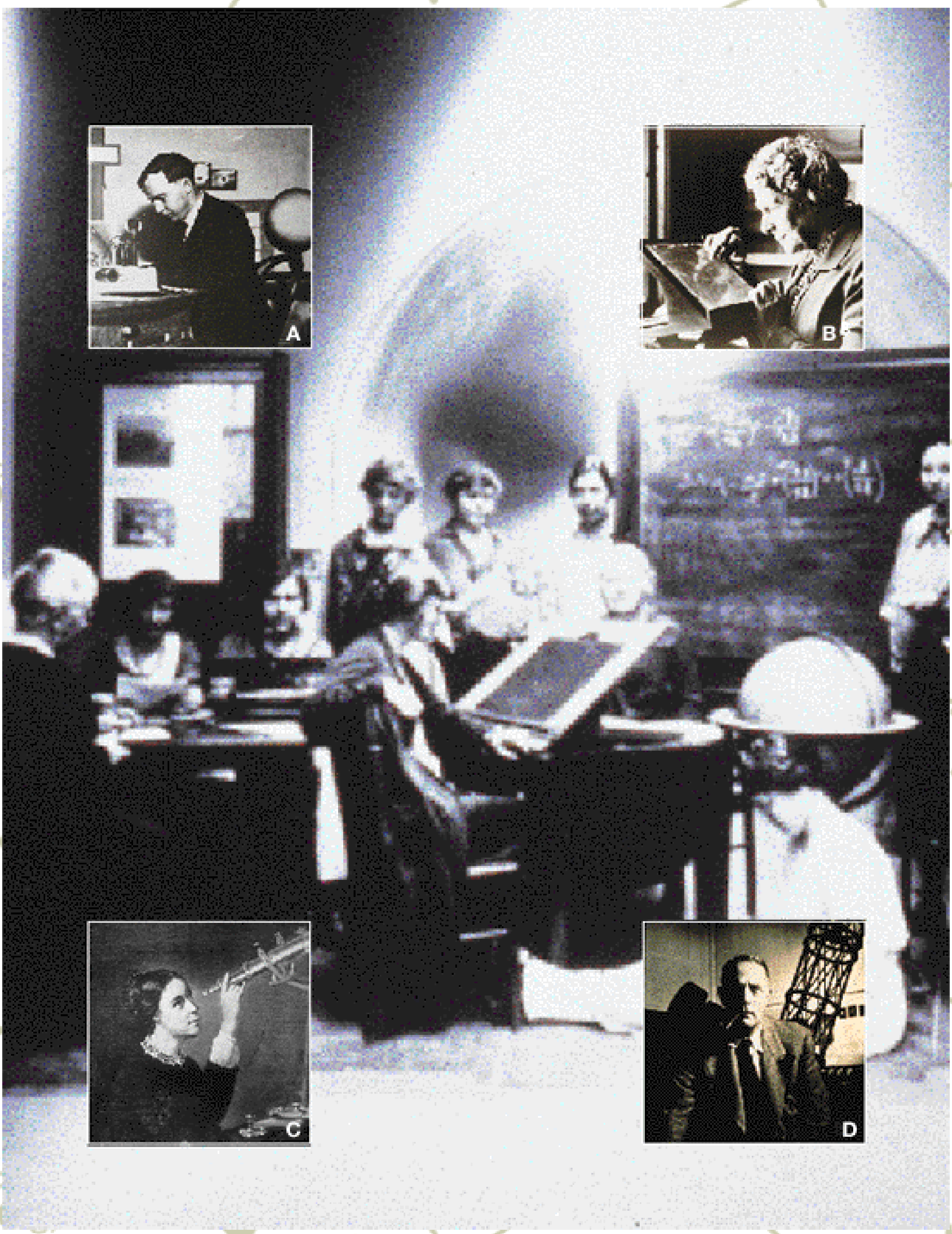
2 THE COPERNICAN REVOLUTION

The Birth of Modern Science



(Background) In an early twentieth-century classroom at Radcliffe College, as at other schools, astronomy came into its own as a viable and important subject.

(Inset A) Harlow Shapley (1885-1972), discovered our place in the "suburbs" of the Milky Way, dispelling the notion that the Sun resides at the center of the universe.

(Inset B) Annie Cannon (1863-1941), one of the greatest astronomical cataloguers of all time, carefully analyzed photographic plates to classify nearly a million stars over the course of fifty years of work at Harvard.

(Inset C) Maria Mitchell (1818-1889) in her observatory on Nantucket Island, made important contributions to several areas of astronomy.

(Inset D) Edwin Hubble (1889-1953), here posing in front of one of the telescopes on Mount Wilson, in California, is often credited with having discovered the expansion of the universe.

LEARNING GOALS

Studying this chapter will enable you to:

1 Relate how some ancient civilizations attempted to explain the heavens in terms of Earth-centered models of the universe.

2 Summarize the role of Renaissance science in the history of astronomy.

3 Explain how the observed motions of the planets led to our modern view of a Sun-centered solar system.

4 Sketch the major contributions of Galileo and Kepler to the development of our understanding of the solar system.

5 State Kepler's laws of planetary motion.

6 Explain how Kepler's laws enable us to construct a scale model of the solar system, and explain the technique used to determine the actual size of the planetary orbits.

7 State Newton's laws of motion and universal gravitation and explain how they account for Kepler's laws.

8 Explain how the law of gravitation enables us to measure the masses of astronomical bodies.

Living in the Space Age, we have become accustomed to the modern view of our place in the universe. Images of our planet taken from space leave little doubt that Earth is round, and no one seriously questions the idea that we orbit the Sun. Yet there was a time, not so long ago, when our ancestors maintained that Earth was flat and lay at the center of all things. Our view of the universe? and of ourselves—has undergone a radical transformation since those early days. Earth has become a planet like many others, and humankind has been torn from its throne at the center of the cosmos and relegated to a rather unremarkable position on the periphery of the Milky Way Galaxy. But we have been amply compensated for our loss of prominence—we have gained a wealth of scientific knowledge in the process. The story of how all this came about is the story of the rise of the scientific method and the genesis of modern astronomy.

NEXT CHAPTER REVIEW

Ø

2.1 Ancient Astronomy

1 Many ancient cultures took a keen interest in the changing nighttime sky. The records and artifacts that have survived until the present make that abundantly clear. But unlike today, the major driving force behind the development of astronomy in those early societies was probably neither scientific nor religious in nature. Instead, it was decidedly practical and very down to earth. Seafarers needed to navigate their vessels, and farmers had to know when to plant their crops. In a very real sense, then, human survival depended on knowledge of the heavens. As a result, the ability to predict the arrival of the seasons, as well as other astronomical events, was undoubtedly a highly prized, and perhaps also jealously guarded, skill.

In Chapter 1 we saw that the human brain's ability to perceive patterns in the stars led to the "invention" of constellations as a convenient means of labeling regions of the celestial sphere. ∞(Sec. 1.2) The realization that these patterns returned to the night sky at the same time each year met the need for a practical means of tracking the seasons. Many separate cultures, all over the world, built large and elaborate structures to serve, at least in part, as primitive calendars. In some cases, the keepers of the secrets of the sky eventually enshrined their knowledge in myth and ritual, and these astronomical sites were often also used for religious rites.

Perhaps the best known such site is *Stonehenge*, located on Salisbury Plain, in England, and shown in Figure 2.1. This ancient stone circle, which today is one of the most popular tourist attractions in Britain, dates from the Stone Age. Researchers believe it was an early astronomical observatory of sorts—not in the modern sense of the term (a place for making new observations and discoveries) but rather a kind of three-dimensional calendar or almanac, enabling its builders and their descendants to identify important dates by means of specific celestial events. Its construction apparently spanned a period of some 17 centuries, beginning around 2800 B.C. Additions and modifications continued up to about 1100 B.C. , indicating its ongoing importance to the Stone Age and later Bronze Age people who built, maintained, and used Stonehenge. The largest stones shown in Figure 2.1 weigh up to 50 tons and were transported from quarries many miles away.

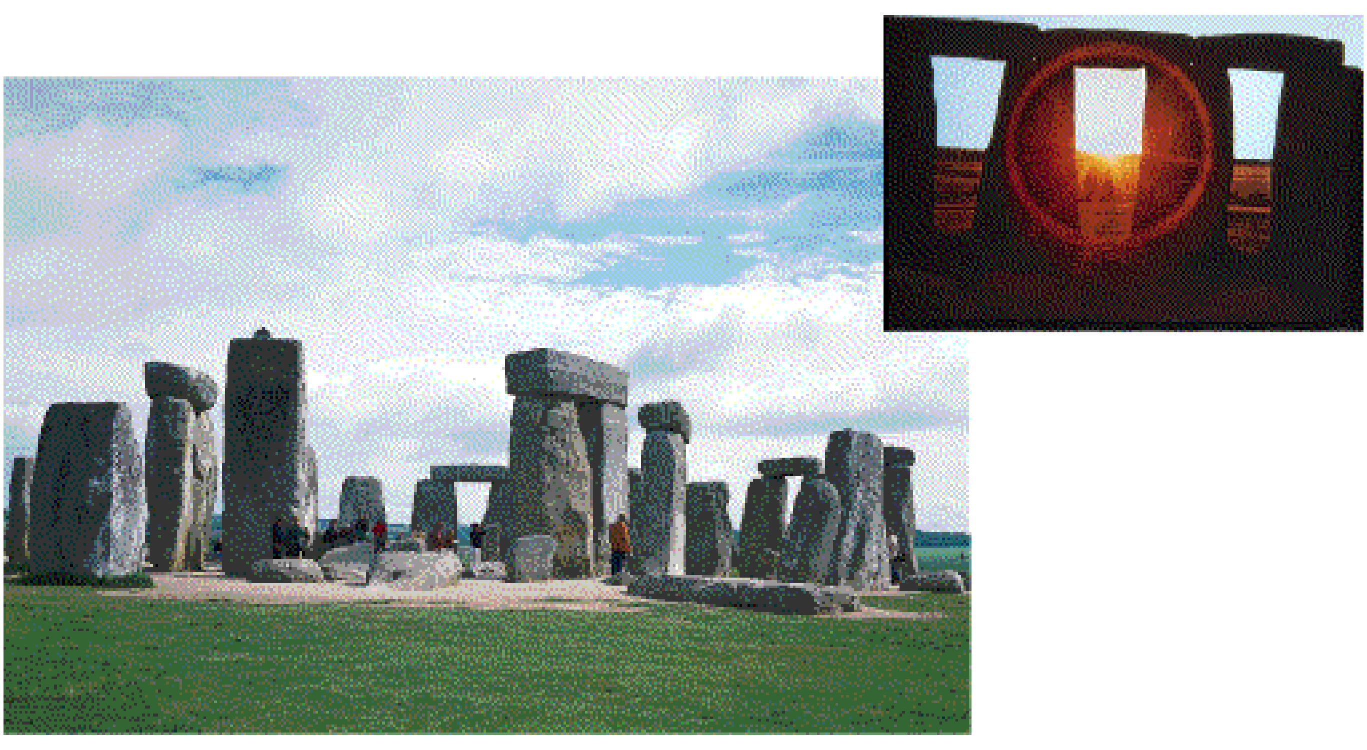


Figure 2.1 *Stonehenge was probably constructed as a primitive calendar and almanac. The fact that the largest stones were carried to the site from many miles away attests to the importance of this structure to its Stone Age builders. The inset shows sunrise at Stonehenge on the summer solstice. As seen from the center of the stone circle, the Sun rose directly over the "heel stone" on the longest day of the year.*

Many of the stones are aligned so that they point toward important astronomical events. For example, the line joining the center of the inner circle to the so-called heel stone, set off at some distance from the rest of the structure, points in the direction of the rising Sun on the summer solstice. Other alignments are related to the rising and setting of the Sun and the Moon at various other times of the year. The accurate alignments (within a degree or so) of the stones of Stonehenge were first noted in the eighteenth century, but it is only relatively recently—in the second half of the twentieth century, in fact—that the scientific community has credited Stone Age technology with the ability to carry out such a precise feat of engineering. While some of Stonehenge's purposes remain uncertain and controversial, the site's function as an astronomical almanac seems well established. Although Stonehenge is the most impressive and the best preserved, other stone circles, found all over Europe, are believed to have performed similar functions.

Many other cultures are now known to have been capable of similarly precise accomplishments. The Big Horn Medicine Wheel in Wyoming (Figure 2.2(a)) is similar to Stonehenge in design—and, presumably, intent—although it is somewhat simpler in execution. The Medicine Wheel's alignments with the rising and setting Sun and with some bright stars indicate that its builders—the Plains Indians—had much more than a passing familiarity with the changing nighttime sky. Figure 2.2(b) shows the Caracol temple, built by the Mayans around A.D. 1000 on Mexico's Yucatan peninsula. This temple is much more sophisticated than Stonehenge, but it probably played a similar role as an astronomical observatory. Its many windows are accurately aligned with astronomical events, such as sunrise and sunset at the solstices and equinoxes and the risings and settings of the planet Venus. Astronomy was of more than mere academic interest to the Mayans, however. Caracol was also the site of countless human sacrifices, carried out when Venus appeared in the morning or evening sky.

(a) (b)

Figure 2.2 *(a) The Big Horn Medicine Wheel, in Wyoming, was built by the Plains Indians. Its spokes and other features are aligned with risings and settings of the Sun and other stars. (b) Caracol temple in Mexico. The many windows of this Mayan construct are aligned with astronomical events, indicating that at least part of Caracol's function was to keep track of the seasons and the heavens.*

The ancient Chinese too observed the heavens. Their astrology attached particular importance to "omens" such as comets and "guest stars —stars that appeared suddenly in the sky and then slowly faded away—and they kept careful and extensive records of such events. Twentieth-century astronomers still turn to the Chinese records to obtain observational data recorded during the Dark Ages (roughly from the fifth to the tenth century A.D.), when turmoil in Europe largely halted the progress of Western science. Perhaps the best-known guest star was one that appeared in A.D. 1054 and was visible in the daytime sky for many months. We now know that the event was actually a *supernova*: the explosion of a giant star, which scattered most of its mass into space. It left behind a remnant that is still detectable today, nine centuries later. The Chinese data are a prime source of historical information for supernova research.

A vital link between the astronomy of ancient Greece and that of medieval Europe was provided by Arab astronomers (Figure 2.3). For six centuries, from the depths of the Dark Ages to the beginning of the Renaissance, Islamic astronomy flourished and grew, preserving and augmenting the knowledge of the Greeks. The Arab influence on modern astronomy is subtle but quite pervasive. Many of the mathematical techniques involved in trigonometry were developed by Muslim astronomers in response to very practical problems, such as determining the precise dates of holy days or the direction of Mecca from any given location on Earth. Astronomical terms like "zenith" and "azimuth" and the names of many stars, such as Rigel, Betelgeuse, and Vega, all bear witness to this extended period of Muslim scholarship.

Figure 2.3 *Arab astronomers at work, as depicted in a medieval manuscript.*

Astronomy is not the property of any one culture, civilization, or era. The same ideas, the same tools, and even the same misconceptions have been invented and reinvented by human societies all over the world, in response to the same basic driving forces. Astronomy came into being because people believed that there was a practical benefit in being able to predict the positions of the stars, but its roots go much deeper than that. The need to understand where we came from, and how we fit into the cosmos, is an integral part of human nature.

NEXT CHAPTER REVIEW

2.2 The Geocentric Universe

The Greeks of antiquity, and undoubtedly civilizations before them, built models of the universe. The study of the workings of the universe on the very largest scales is called **cosmology**. Today, cosmology entails looking at the universe on scales so large that even entire galaxies can be regarded as mere points of light scattered throughout space. To the Greeks, however, the universe was basically the *solar system*—namely, the Sun, Earth, Moon, and the planets known at that time. The stars beyond were surely part of the universe, but they were considered to be fixed, unchanging beacons on a mammoth celestial dome. The Greeks did not consider the Sun, the Moon, and the planets to be part of the celestial sphere, however. Those objects had patterns of behavior that set them apart.

Greek astronomers observed that over the course of a night, the stars slid smoothly across the sky. Over the course of a month, the Moon moved smoothly and steadily along its path on the sky relative to the stars, passing through its familiar cycle of phases. Over the course of a year, the Sun progressed along the ecliptic at an almost constant rate, varying little in brightness from day to day. In short, the behavior of both Sun and Moon seemed fairly simple and orderly. But ancient astronomers were also aware of five other bodies in the sky—the planets Mercury, Venus, Mars, Jupiter, and Saturn—whose behavior was not so easy to grasp. Their motions ultimately led to the downfall of an entire theory of the solar system and to a fundamental change in humankind's view of the universe.

Planets do not behave in as regular and predictable a fashion as the Sun, Moon, and stars. They vary in brightness, and they don't maintain a fixed position in the sky. Unlike the Sun and the Moon, the planets seem to wander around the celestial sphere—indeed, the word planet derives from the Greek word *planetes*, meaning "wanderer. " Planets never stray far from the ecliptic and generally traverse the celestial sphere from west to east, as the Sun does. However, they seem to speed up and slow down during their journeys, and at times they even appear to loop back and forth relative to the stars, as shown in Figure 2.4. In other words, there are periods when a planet's eastward motion (relative to the stars) stops, and the planet appears to move westward in the sky for a month or two before reversing direction again and continuing on its eastward journey. Motion in the eastward sense is usually referred to as *direct*, or *prograde*, motion; the backward (westward) loops are known as **retrograde motion**.

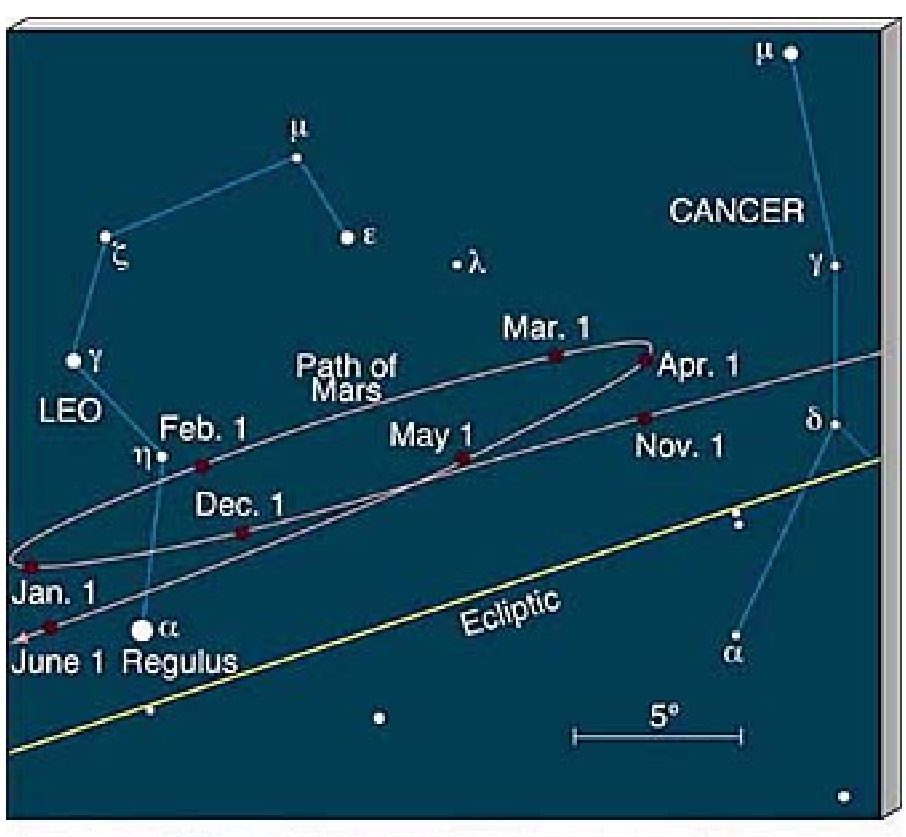


Figure 2.4 Most of the time, planets move from west to east relative to the background stars. Occasionally, however, they change direction and temporarily undergo retrograde motion before looping back. The art above shows an actual retrograde loop in the motion of the planet Mars. The inset above depicts the movements of several planets over the course of several years, as reproduced on the inside dome of a planetarium. The motion of the planets relative to the stars (represented as unmoving points) produces continuous streaks on the planetarium "sky."

Like the Moon, the planets produce no light of their own; instead, they shine by reflected sunlight. Ancient astronomers correctly reasoned that the apparent brightness of a planet in the night sky is related to its distance from Earth—planets appear brightest when closest to us. However, the planets Mars, Jupiter, and Saturn are always brightest during the retrograde portions of their orbits. The challenge facing astronomers was to explain the observed motions of the planets and to relate those motions to the variations in planetary brightness.

The earliest models of the solar system followed the teachings of the Greek philosopher Aristotle (384–322 b.c.) and were **geocentric** in nature, meaning that Earth lay at the center of the universe and that all other bodies moved around it. (Figures 1.7 and 1.10a illustrate the basic geocentric view.) ∞(Sec. 1.2) These models employed what Aristotle, and Plato before him, had taught was the perfect form: the circle. The simplest possible description—uniform motion around a circle having Earth at its center—provided a fairly good approximation to the orbits of the Sun and the Moon, but it could not account for the observed variations in planetary brightness or their retrograde motion. A more complex model was needed to describe the planets.

In the first step toward this new model, each planet was taken to move uniformly around a small circle, called an **epicycle**, whose *center* moved uniformly around Earth on a second and larger circle, known as the **deferent** (Figure 2.5). The motion was now composed of two separate circular orbits, creating the possibility that, at some times, the planet's apparent motion could be retrograde. Also, the distance from the planet to Earth would vary, accounting for changes in brightness. By tinkering with the relative sizes of epicycle and deferent, with the planet's speed on the epicycle, and with the epicycle's speed along the deferent, early astronomers were able to bring this "epicyclic" motion into fairly good agreement with the observed paths of the planets in the sky. Moreover, this model had good predictive power, at least to the accuracy of observations at the time.

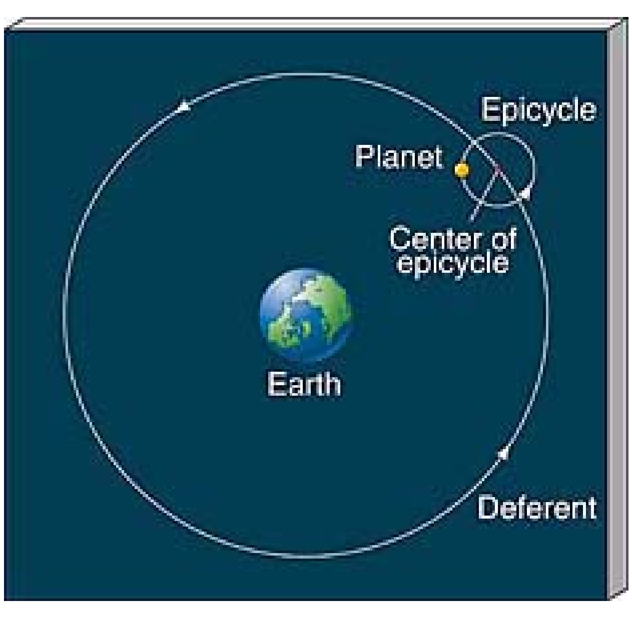


Figure 2.5 In the geocentric model of the solar system, the observed motions of the planets made it impossible to assume that they moved on simple circular paths around Earth. Instead, each planet was thought to follow a small circular orbit (the epicycle) about an imaginary point that itself traveled in a large, circular orbit (the deferent) about Earth.

However, as the number and the quality of observations increased, it became clear that the simple epicyclic model was not perfect. Small corrections had to be introduced to bring it into line with new observations. The center of the deferents had to be shifted slightly from Earth's center, and the motion of the epicycles had to be imagined uniform with respect not to Earth but to yet another point in space. Around a.d. 140, a Greek astronomer named Ptolemy constructed perhaps the best geocentric model of all time. Illustrated in simplified form in Figure 2.6, it explained remarkably well the observed paths of the five planets then known, as well as the paths of the Sun and the Moon. However, to achieve its explanatory and predictive power, the full **Ptolemaic model** required a series of no fewer than 80 distinct circles. To account for the paths of the Sun, the Moon, and all the nine planets (and their moons) that we know today would require a vastly more complex set. Nevertheless, Ptolemy's text on the topic, *Syntaxis* (better known today by its Arabic name *Almagest*—"the greatest"), provided the intellectual framework for all discussion of the universe for well over a thousand years.

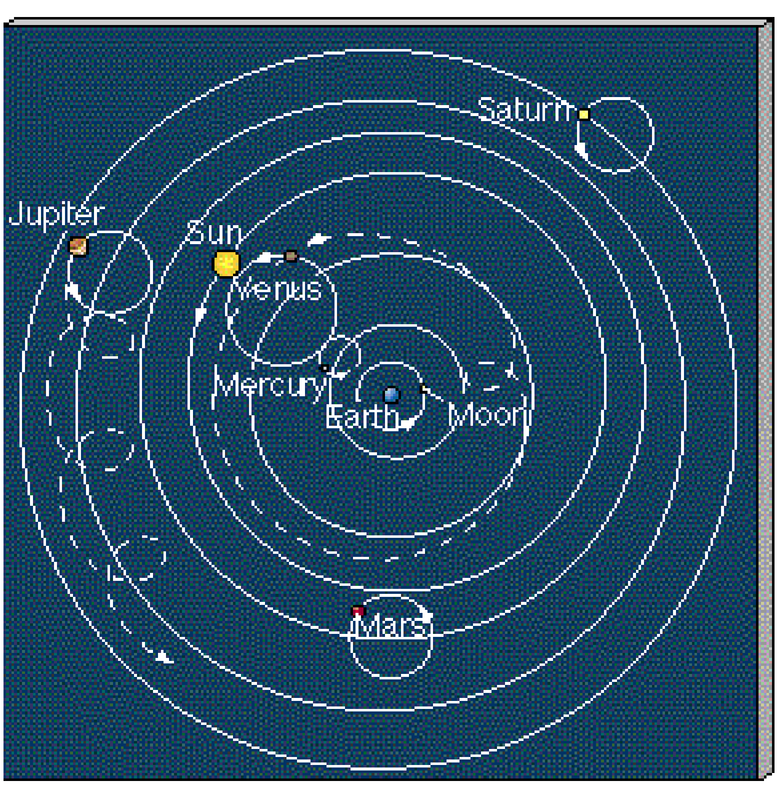


Figure 2.6 The basic features, drawn roughly to scale, of the geocentric model of the inner solar system that enjoyed widespread popularity prior to the Renaissance. To avoid confusion, we have drawn partial paths (dashed) of only two planets, Venus and Jupiter.

Today, our scientific training leads us to seek simplicity, because simplicity in the physical sciences has so often proved to be an indicator of truth. We would regard the intricacy of a model as complicated as the Ptolemaic system as a clear sign of a fundamentally flawed theory. With the benefit of hindsight, we now recognize that the major error lay in the assumption of a geocentric universe. This was compounded by the insistence on uniform circular motion, whose basis was largely philosophical, rather than scientific, in nature.

Actually, history records that some ancient Greek astronomers reasoned differently about the motions of heavenly bodies. Foremost among them was Aristarchus of Samos (310–230 b.c.), who proposed that all the planets, including Earth, revolve around the Sun and, furthermore, that Earth rotates on its axis once each day. This, he argued, would create an *apparent* motion of the sky—a simple idea that is familiar to anyone who has ridden on a merry-go-round and watched the landscape appear to move past in the opposite direction. However, Aristarchus's description of the heavens, though essentially correct, did not gain widespread acceptance during his lifetime. Aristotle's influence was too strong, his followers too numerous, his writings too comprehensive. The geocentric model went largely unchallenged until the sixteenth century a.d.

The Aristotelian school did present some simple and (at the time) compelling arguments in favor of their views. First, of course, Earth doesn't *feel* as if it's moving. And if it were, wouldn't there be a strong wind as we moved at high speed around the Sun? Then again, considering that the vantage point from which we view the stars changes over the course of a year, why don't we see stellar parallax? Nowadays we might be inclined to dismiss the first two points as merely naive, but the third is a valid argument and the reasoning is essentially sound. We now know that there *is* stellar parallax as Earth orbits the Sun. However, because the stars are so distant, it amounts to less than 1", even for the closest stars. Early astronomers simply would not have noticed it. We will encounter many other instances in astronomy where correct reasoning has led to the wrong conclusions because it was based on inadequate data.

PREVIOUS NEXT CHAPTER REVIEW

2.3 The Heliocentric Model of the Solar System

2 The Ptolemaic picture of the universe survived, more or less intact, for almost 13 centuries, until a sixteenth-century Polish cleric, Nicholas Copernicus (Figure 2.7), rediscovered Aristarchus's **heliocentric** (Sun-centered) model and showed how, in its harmony and organization, it provided a more natural explanation of the observed facts than did the tangled geocentric cosmology. Copernicus asserted that Earth spins on its axis and, like the other planets, orbits the Sun. Only the Moon, he said, orbits Earth. Not only does this model explain the observed daily and seasonal changes in the heavens, as we saw in Chapter 1, but it also naturally accounts for planetary retrograde motion and brightness variations. The critical realization that Earth is not at the center of the universe is now known as the **Copernican revolution**. The seven crucial statements that form its foundation are summarized in *Interlude 2-1*.

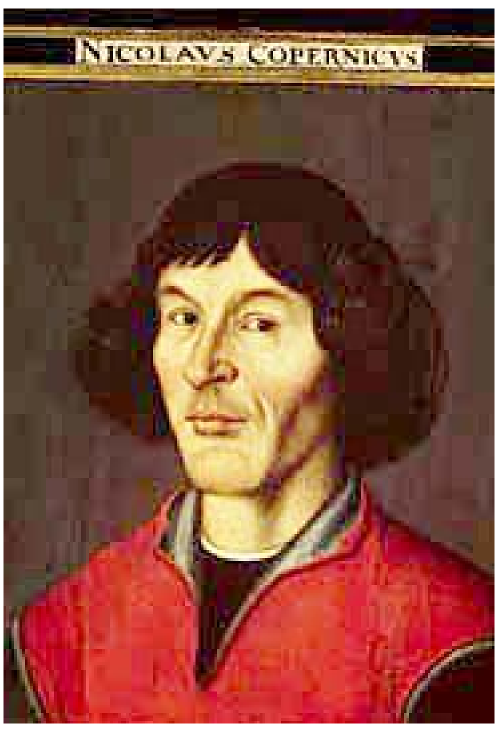


Figure 2.7 Nicholas Copernicus (1473–1543).

Figure 2.8 shows how the Copernican view explains both the varying brightness of a planet (in this case, Mars) and its observed looping motions. If we suppose that Earth moves faster than Mars, then every so often Earth "overtakes" that planet. Mars will then appear to move backward in the sky, in much the same way as a car we overtake on the highway seems to slip backward relative to us. Notice that in the Copernican picture the planet's looping motions are only apparent; in the Ptolemaic view, they were real.

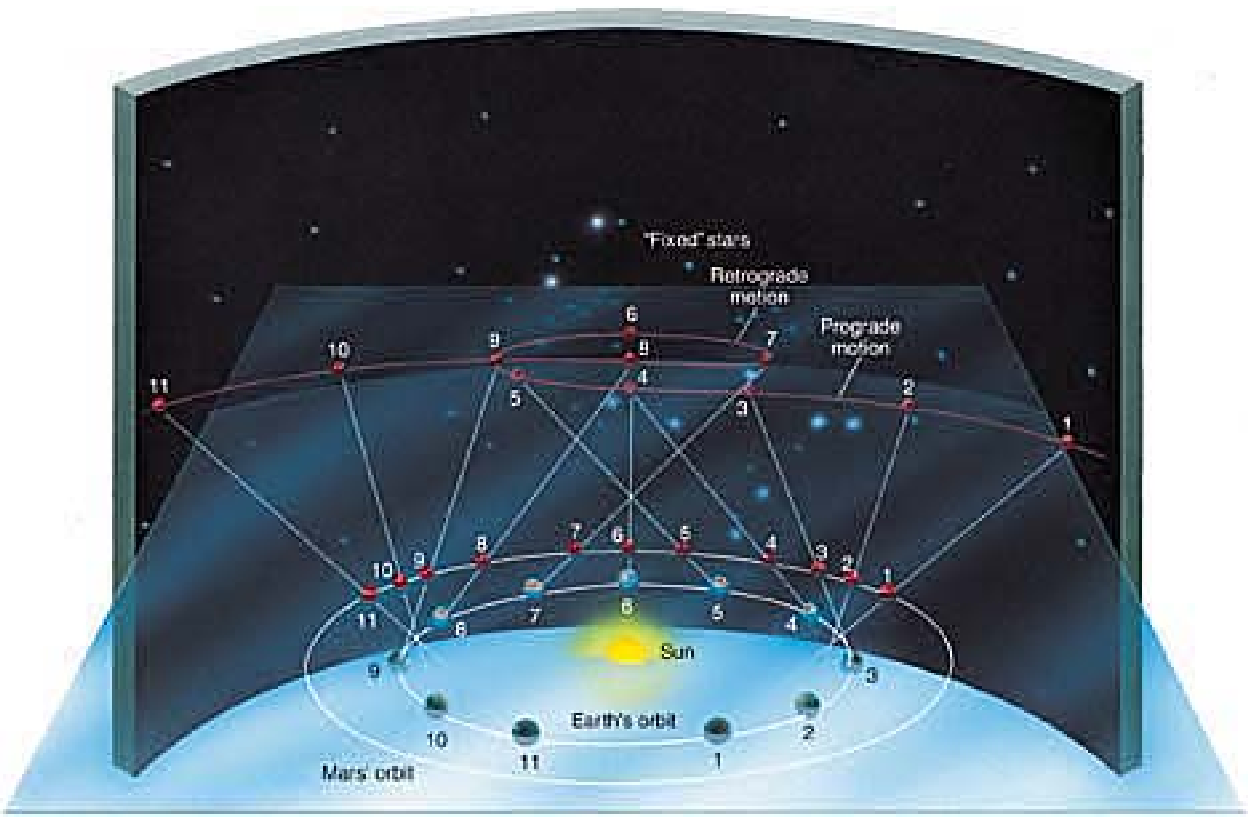


Figure 2.8 The Copernican model of the solar system explains the varying brightnesses of the planets, something the Ptolemaic system largely ignored. Here, for example, when Earth and Mars are relatively close to each other in their respective orbits (as at position 6), Mars seems brighter; when farther away (as at position 1), Mars seems dimmer. Also, because the line of sight from Earth to Mars changes as the two planets smoothly orbit the Sun, Mars appears to loop back and forth, undergoing retrograde motion. The line of sight changes because Earth, on the inside track, moves faster in its orbit than Mars moves along its path.

Copernicus's major motivation for introducing the heliocentric model was simplicity. Even so, he was still influenced by Greek thinking and clung to the idea of circles to model the planets' motions. As a result, in order to bring his theory into agreement with observations, he was forced to retain the idea of epicyclic motion, although with the deferent centered on the Sun rather than on Earth, and with smaller epicycles than in the Ptolemaic picture. Thus, he retained unnecessary complexity and actually gained little in accuracy over the geocentric model. The heliocentric model did rectify some small discrepancies and inconsistencies in the Ptolemaic system, but for Copernicus, the primary attraction of heliocentricity was its simplicity, its being "more pleasing to the mind." His theory was more something he *felt* than he could *prove*. To the present day, scientists still are guided by simplicity, symmetry, and beauty in modeling all aspects of the universe.

Despite the support of some observational data, neither his fellow scholars nor the general public easily accepted Copernicus's model. For the learned, heliocentricity went against the grain of much previous thinking and violated many of the religious teachings of the time, largely because it relegated Earth to a noncentral and undistinguished place within the solar system and the universe. And Copernicus's work had little impact on the general populace of his time, at least in part because it was published in Latin (the standard language of academic discourse at the time), which most people could not read. Only after Copernicus's death, when others—notably Galileo Galilei—popularized his ideas, did the Roman Catholic church take them seriously enough to bother banning them. Copernicus's writings on the heliocentric universe were placed on the *Index of Prohibited Books* in 1616, 73 years after they were first published. They remained there until the end of the eighteenth century.

PREVIOUS NEXT CHAPTER REVIEW

INTERLUDE 2-1 The Foundations of the Copernican Revolution

The following seven points are essentially Copernicus's own words. The italicized material is additional explanation.

1. The celestial spheres do not have just one common center. *Specifically, Earth is not at the center of everything*.
2. The center of Earth is not the center of the universe but is instead only the center of gravity and of the lunar orbit.
3. All the spheres revolve around the Sun. *By spheres, Copernicus meant the planets*.
4. The ratio of Earth's distance from the Sun to the height of the firmament is so much smaller than the ratio of Earth's radius to the distance to the Sun that the distance to the Sun is imperceptible when compared with the height of the firmament. *By firmament, Copernicus meant the distant stars. The point he was making is that the stars are very much farther away than the Sun*.
5. The motions appearing in the firmament are not its motions but those of Earth. Earth performs a daily rotation around its fixed poles while the firmament remains immobile as the highest heaven. *Because the stars are so far away, any apparent motion we see in them is the result of Earth's rotation*.
6. The motions of the Sun are not its motions but the motion of Earth. *Similarly, the Sun's apparent daily and yearly motion are actually due to the various motions of Earth*.
7. What appears to us as retrograde and forward motion of the planets is not their own but that of Earth. *The heliocentric picture provides a natural explanation for retrograde planetary motion, again as a consequence of Earth's motion*.

2.4 The Laws of Planetary Motion

In the century following the death of Copernicus and the publication of his theory of the solar system, two scientists—Johannes Kepler and Galileo Galilei—made indelible imprints on the study of astronomy. Contemporaries, they were aware of each other's work and corresponded from time to time about their theories. Each achieved fame for his discoveries and, in his own way, made great strides in popularizing the Copernican viewpoint, yet in their approaches to astronomy they were as different as night and day. Kepler (Figure 2.9), a German mathematician and astronomer, was a pure theorist. His groundbreaking work that so clarified our knowledge of planetary motion was based almost entirely on the observations of others (partly because of Kepler's own poor eyesight). In contrast, Galileo was in many ways the first "modern" astronomer. He used emerging technology, in the form of the telescope, to achieve new insights into the universe. We will study some of Galileo's accomplishments, and their consequences, in Section 2.5.

Figure 2.9 Johannes Kepler (1571—1630).

BRAHE'S COMPLEX DATA

3 Kepler's work was based on an extensive collection of data compiled by Tycho Brahe (1546—1601), Kepler's employer and arguably one of the greatest observational astronomers that has ever lived. Tycho, as he is often called, was both an eccentric aristocrat and a skillful observer. Born in Denmark, he was educated at some of the best universities in Europe, where he studied astrology, alchemy, and medicine. Most of his observations, which predated the invention of the telescope by several decades, were made at his own observatory, named *Uraniborg*, in Denmark (Figure 2.10). There, using instruments of his own design, Tycho maintained meticulous and accurate records of the stars, planets, and other noteworthy celestial events.

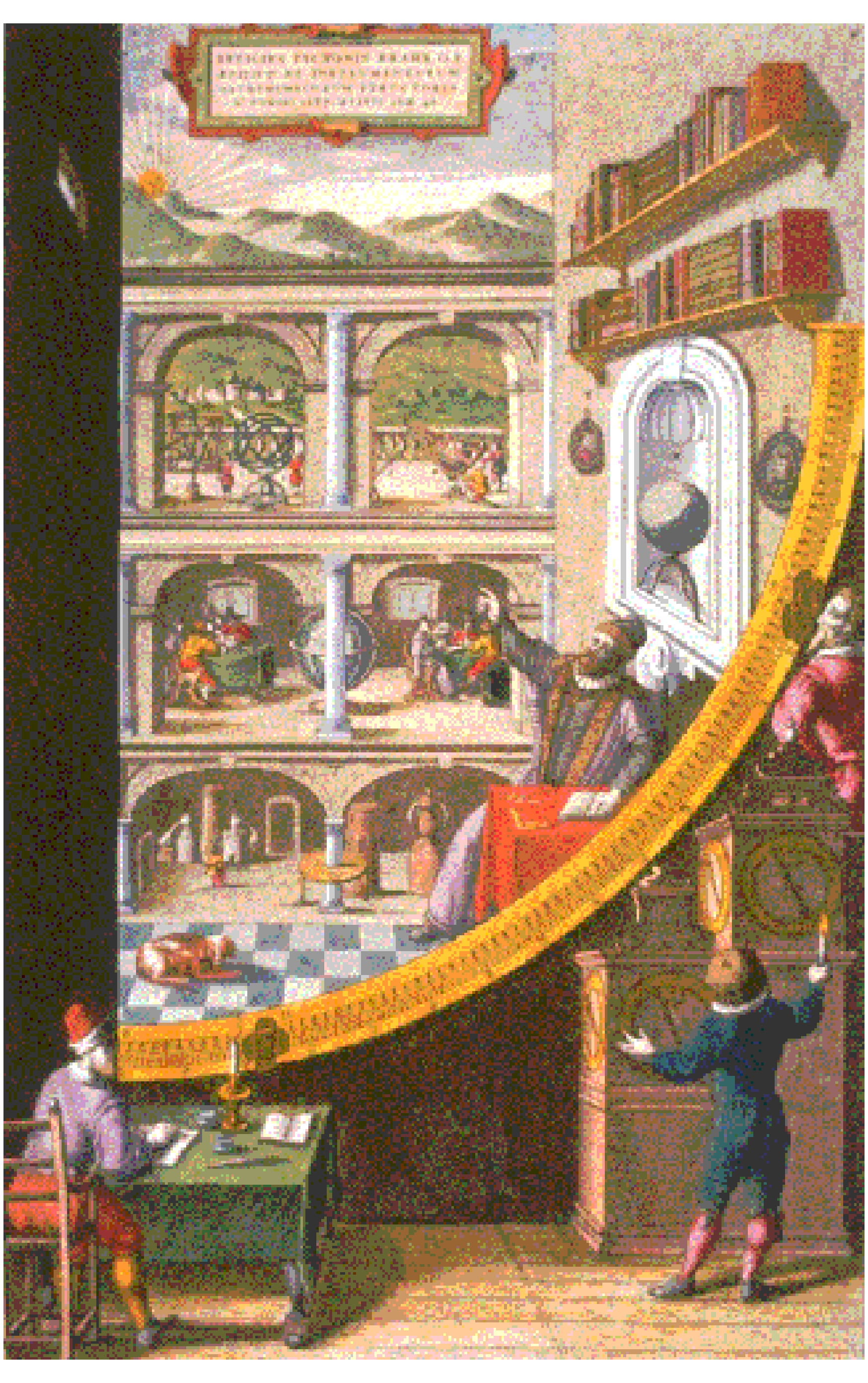


Figure 2.10 Tycho Brahe in his observatory Uraniborg, on the island of Hveen, in Denmark.

In 1597, having fallen out of favor with the Danish court, Tycho moved to Prague, which happens to be fairly close to Graz, in Austria, where Kepler lived and worked. Kepler joined Tycho in Prague in 1600. There Kepler was put to work trying to find a theory that could explain Brahe's planetary data. When Tycho died a year later, Kepler inherited not only Brahe's position as Imperial Mathematician of the Holy Roman Empire (then located in Eastern Europe) but also his priceless possession: the accumulated observations of the planets, spanning several decades. Tycho's observations, though made with the naked eye, were nevertheless of very high quality. In most cases, his measured positions of stars and planets were accurate to within about 1°. Kepler set to work seeking a unifying principle to explain in detail the motions of the planets, without the need for epicycles. The effort was to occupy much of the remaining 29 years of his life.

Kepler had already accepted the heliocentric picture of the solar system. His goal was to find a simple and elegant description of the solar system, within the Copernican framework, that fit Tycho's complex mass of detailed observations. In the end, he found it necessary to abandon Copernicus's original simple idea of circular planetary orbits. However, an even greater simplicity emerged as a result. After long years studying Brahe's planetary data, and after many false starts and blind alleys, Kepler developed the laws of planetary motion that now bear his name.

Kepler determined the shape of each planet's orbit by triangulation—not from different points on Earth, but from different points on Earth's orbit, using observations made at many different times of the year. (Sec. 1.9) By using a portion of Earth's orbit as a baseline, Kepler was able to measure the relative sizes of the other planetary orbits. Noting where the planets were on successive nights, he found the speeds at which the planets move. We do not know how many geometric shapes Kepler tried for the orbits before he hit upon the correct one. His difficult task was made even more complex because he had to determine Earth's own orbit, too. Nevertheless, he eventually succeeded in summarizing the motions of all the known planets, including Earth, in just three laws, the **laws of planetary motion**.

KEPLER'S SIMPLE LAWS

5 *Kepler's first law* has to do with the *shapes* of the planetary orbits:

> The orbital paths of the planets are elliptical (*not* circular), with the Sun at one focus.

An **ellipse** is simply a flattened circle. Figure 2.11 illustrates a means of constructing an ellipse using a piece of string and two thumbtacks. Each point at which the string is pinned is called a **focus** (plural: *foci*) of the ellipse. The long axis of the ellipse, containing the two foci, is known as the *major axis*. Half the length of this long axis is referred to as the **semi-major axis**; it is a measure of the ellipse's size. The **eccentricity** of the ellipse is the ratio of the distance between the foci to the length of the major axis. The length of the semi-major axis and the eccentricity are all we need to describe the size and shape of a planet's orbital path (*see* More Precisely 2-1). A circle is a special kind of ellipse in which the two foci happen to coincide, so the eccentricity is zero. The semi-major axis of a circle is simply its radius.

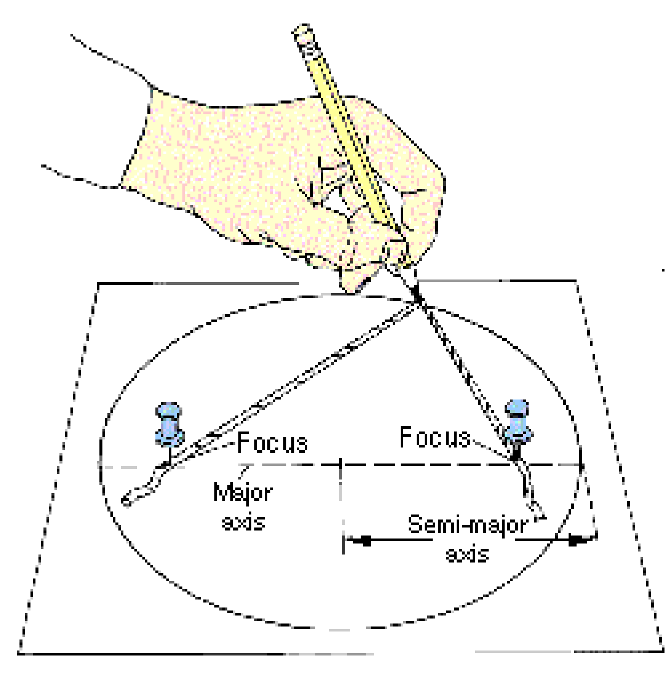


Figure 2.11 Any ellipse can be drawn with the aid of a string, a pencil, and two thumbtacks. The wider the separation of the foci, the more elongated, or eccentric, is the ellipse. In the special case where the two foci are at the same place, the drawn curve is a circle.

In fact, no planet's elliptical orbit is nearly as elongated as the one shown in Figure 2.11. With two exceptions (the paths of Mercury and Pluto), planetary orbits in our solar system have such small eccentricities that our eyes would have trouble distinguishing them from true circles. Only because the orbits are so nearly circular were the Ptolemaic and Copernican models able to come as close as they did to describing reality.

Kepler's substitution of elliptical for circular orbits was no small advance. It amounted to abandoning an aesthetic bias—the Aristotelian belief in the perfection of the circle—that had governed astronomy since Greek antiquity. Even Galileo Galilei, not known for his conservatism in scholarly matters, clung to the idea of circular motion and never accepted that the planets move on elliptical paths.

Kepler's second law, illustrated in Figure 2.12, addresses the speed at which a planet traverses different parts of its orbit:

> An imaginary line connecting the Sun to any planet sweeps out equal areas of the ellipse in equal intervals of time.

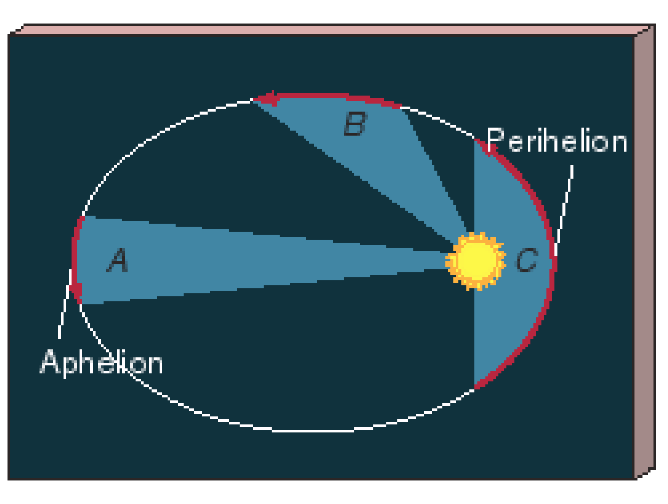


Figure 2.12 A diagram illustrating Kepler's second law: Equal areas are swept out in equal intervals of time. The three shaded areas (A, B, and C) are equal. Note that an object would travel the length of each of the three arrows in the same amount of time. Therefore, planets move faster when closer to the Sun.

While orbiting the Sun, a planet traces the arcs labeled *A*, *B*, and *C* in Figure 2.12 in equal times. Notice, however, that the distance traveled by the planet along arc *C* is greater than the distance traveled along arc *A* or arc *B*. Because the time is the same and the distance is different, the speed must vary. When a planet is close to the Sun, as in sector *C*, it moves much faster than when farther away, as in sector *A*.

By taking into account the relative speeds and positions of the planets in their elliptical orbits about the Sun, Kepler's first two laws explained the variations in planetary brightness and some observed peculiar nonuniform motions that could not be accommodated within the assumption of circular motion, even with the inclusion of epicycles. Gone at last were the circles within circles that rolled across the sky. Kepler's modification of the Copernican theory to allow the possibility of elliptical orbits both greatly simplified the model of the solar system and at the same time provided much greater predictive accuracy than had previously been possible. Note, by the way, that these laws are not restricted to planets. They apply to *any* orbiting object. Spy satellites, for example, move very rapidly as they swoop close to Earth's surface not because they are propelled with powerful on-board rockets but because their highly eccentric orbits are governed by Kepler's laws.

Kepler published his first two laws in 1609, stating that he had proved them only for the orbit of Mars. Ten years later, he extended them to all the then-known planets (Mercury, Venus, Earth, Mars, Jupiter, and Saturn) and added a third law relating the size of a planet's orbit to its sidereal orbital **period**—the time needed for the planet to complete one circuit around the Sun. *Kepler's third law* states that

> The square of a planet's orbital period is proportional to the cube of its semi-major axis.

This law becomes particularly simple when we choose the (Earth) year as our unit of time and the *astronomical unit* as our unit of length. One **astronomical unit** (A.U.) is the semi-major axis of Earth's orbit around the Sun—essentially the average distance between Earth and the Sun. Like the light year, the astronomical unit is custom-made for the vast distances encountered in astronomy. Using these units for time and distance, we can write Kepler's third law for any planet as

$$P^2 \text{ (in Earth years)} = a^3 \text{ (in astronomical units)},$$

where P is the planet's sidereal orbital period, and $a$is the length of its semi-major axis. The law implies that a planet's "year" Pincreases more rapidly than does the size of its orbit a. For example, Earth, with an orbital semi-major axis of 1 A.U., has an orbital period of 1 Earth year. The planet Venus, orbiting at a distance of roughly 0.7 A.U., takes only 0.6 Earth years—about 225 days—to complete one circuit. By contrast, Saturn, almost 10 A.U. out, takes considerably more than 10 Earth years—in fact, nearly 30 years—to orbit the Sun just once.

Table 2.1 presents basic data describing the orbits of the nine planets now known. Renaissance astronomers knew these properties for the innermost six planets and used them to construct the currently accepted heliocentric model of the solar system. The second column presents each planet's orbital semi-major axis, measured in astronomical units; the third column gives the orbital period, in Earth years. The fourth column lists the planets' orbital eccentricities. For purposes of verifying Kepler's third law, the rightmost column lists the ratio P^2/a^3. As we have just seen, in the units used in the table, the third law implies that this number should equal 1 in all cases.

TABLE 2.1 Some Solar System Dimensions

PLANET	ORBITAL SEMI-MAJOR AXIS, a (astronomical units)	ORBITAL PERIOD,P (Earth years)	ORBITAL ECCENTRICITY	P^2/a^3
Mercury	0.387	0.241	0.206	1.002
Venus	0.723	0.615	0.007	1.001
Earth	1.000	1.000	0.017	1.000
Mars	1.524	1.881	0.093	1.000
Jupiter	5.203	11.86	0.048	0.999
Saturn	9.537	29.42	0.054	0.998
Uranus	19.19	83.75	0.047	0.993
Neptune	30.07	163.7	0.009	0.986
Pluto	39.48	248.0	0.249	0.999

The main points to be grasped from Table 2.1 are these: (1) with the exception of Mercury and Pluto, the planets' orbits are very nearly circular (that is, their eccentricities are close to zero), and (2) the farther a planet is from the Sun, the greater is its orbital period, in precise agreement with Kepler's third law to within the four-digit accuracy of the numbers in the table. (The small but significant deviations of P^2/a^3 from 1 in the cases of Uranus and Neptune are caused by the gravitational attraction between those two planets; see Chapter 13.) For example, in the case of Pluto, verify for yourself that $39.53^3 = 248.6^2$ (at least, to three significant figures). Most important, note that Kepler's laws are obeyed by *all* the known planets, *not just by the six on which he based his conclusions*.

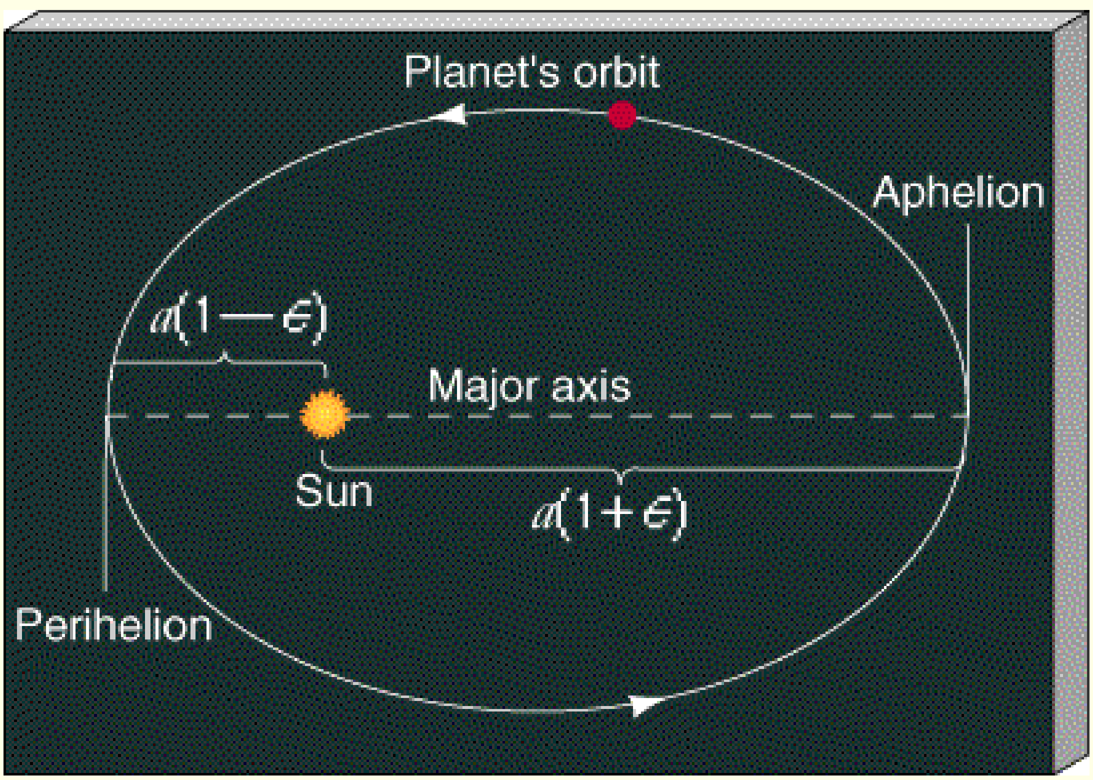
MORE PRECISELY 2-1 Some Properties of Planetary Orbits

Two numbers—semi-major axis and eccentricity—are all that are needed to describe the size and shape of a planet's orbital path. From them we can derive many other useful quantities. Two of the most important are the planet's *perihelion* (its point of closest approach to the Sun) and its *aphelion* (greatest distance from the Sun). From the definitions presented in the text, it follows that if the planet's orbit has semi-major axis a and eccentricity e, its perihelion is at a distance $a(1—e)$ from the Sun, while its aphelion is at $a(1 + e)$. These points and distances are illustrated in the accompanying figure.

Note that while the Sun resides at one focus, the other focus is empty and has no particular significance. Thus, for example, a (hypothetical) planet with a semi-major axis of 400 million km and an eccentricity of 0.5 (the eccentricity of the ellipse shown in the diagram) would range between 400 × (1—0.5) = 200 million km and 400 × (1 + 0.5) = 600 million km from the Sun over the course of one complete orbit. With e= 0.9, the range would be 40—760 million km, and so on.

No planet has an orbital eccentricity as large as 0.5—the planet with the most eccentric orbit is Pluto, with e= 0.248 (see Table 2.1). However,

many meteoroids, and all comets (see Chapter 14) have eccentricities considerably greater than this. In fact, most comets visible from Earth have eccentricities very close to 1. Their highly elongated orbits approach within a few A.U. of the Sun at perihelion, yet these tiny frozen worlds spend most of their time far beyond the orbit of Pluto.



2.5 The Birth of Modern Astronomy

At about the same time as Kepler was developing his laws of planetary motion, Galileo Galilei (Figure 2.13) was finding fame—and notoriety—as an outspoken proponent of the Copernican system. Galileo was an Italian mathematician and philosopher. By being willing to perform experiments to test his ideas—a rather radical approach in those days (*see* Interlude 2-2)—and by embracing the brand-new technology of the telescope, he revolutionized the way in which science was done, so much so that he is now widely regarded as the father of experimental science.

Figure 2.13 *Galileo Galilei (1564—1642).*

GALILEO'S HISTORIC OBSERVATIONS

4 The telescope was invented in Holland in the early seventeenth century. Hearing of the invention (but without having seen one), Galileo built a telescope for himself in 1609 and aimed it at the sky. What he saw conflicted greatly with the philosophy of Aristotle and provided much new data to support the ideas of Copernicus.*

**In fact, Galileo had already abandoned Aristotle in favor of Copernicus, although he had not published these beliefs at the time he began his telescopic observations.*

Using his telescope, Galileo discovered that the Moon had mountains, valleys, and craters—terrain in many ways reminiscent of that on Earth. Looking at the Sun (something that should *never* be done directly, and which eventually blinded Galileo), he found imperfections—dark blemishes now known as *sunspots*. Furthermore, by noting the changing appearance of these sunspots from day to day, he inferred that the Sun *rotates*, approximately once per month, around an axis roughly perpendicular to the ecliptic plane. These observations ran directly counter to the orthodox wisdom of the day.

In studying the planet Jupiter, Galileo saw four small points of light, invisible to the naked eye, orbiting it, and realized that they were moons. To Galileo, the fact that another planet had moons provided the strongest support for the Copernican model; clearly, Earth was not the center of all things. He also found that Venus shows a complete cycle of phases, like those of our Moon, a finding that could be explained only by the planet's motion around the Sun (Figure 2.14). These observations were further strong evidence that Earth is not the center of the solar system, and that at least one planet orbited the Sun.

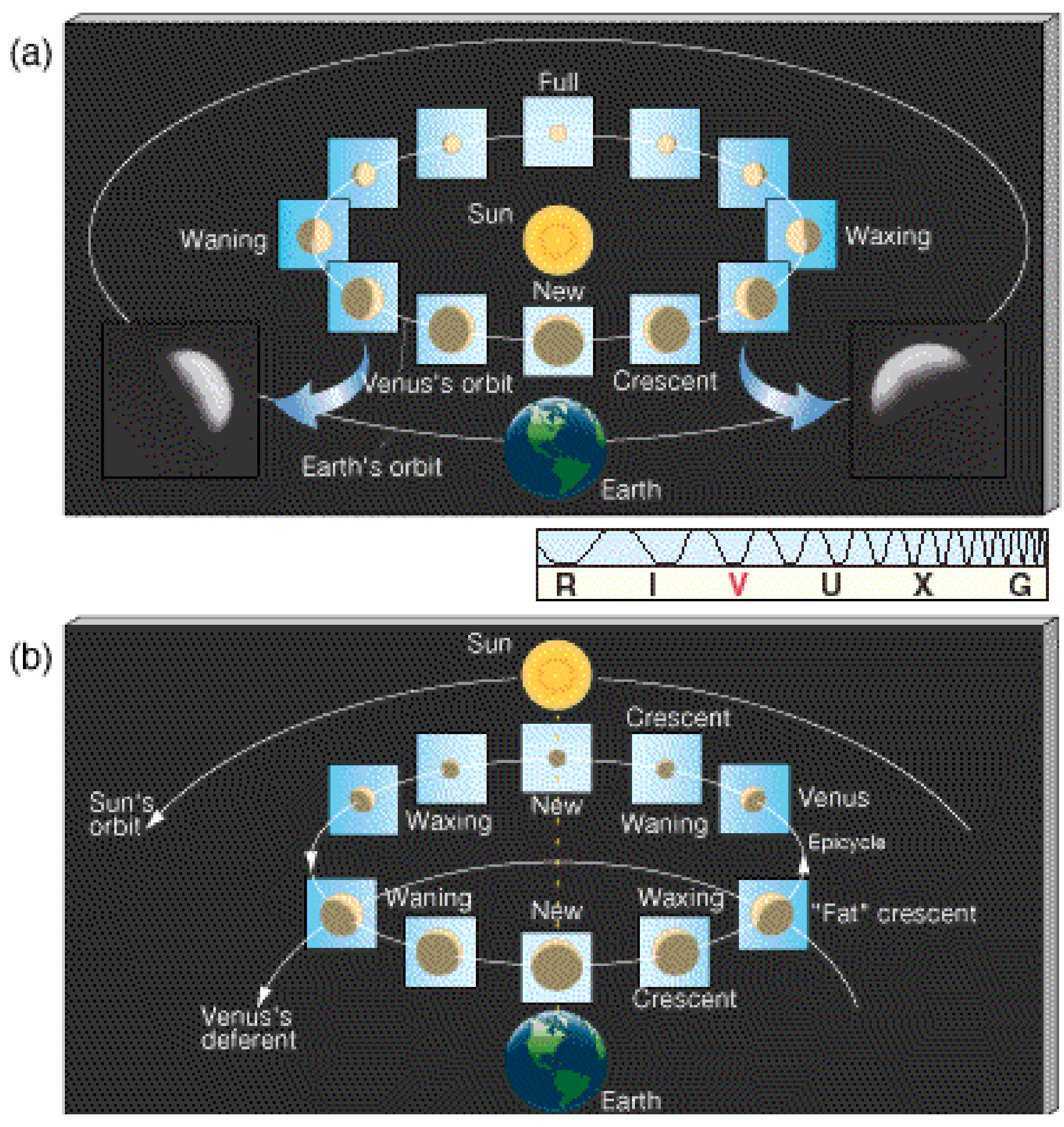


Figure 2.14 *(a) The phases of Venus, rendered at different points in the planet's orbit. If Venus orbits the Sun and is closer to the Sun than is Earth, as Copernicus maintained, then Venus should display phases, much as our Moon does. As shown here, when directly between Earth and the Sun, Venus's unlit side faces us, and the planet is invisible to us. As Venus moves in its orbit (at a faster speed than Earth moves in its orbit), progressively more of its illuminated face is visible from Earth. Note also the connection between orbital phase and the apparent size of the planet. Venus seems much larger in its crescent phase than when it is full because it is much closer to us during its crescent phase. (The insets at bottom left and right are actual photographs of Venus at two of its crescent phases.) (b) The Ptolemaic model (see also Figure 2.6) is unable to account for these observations. In particular, the full phase of the planet cannot be explained. Seen from Earth, Venus reaches only a "fat crescent" phase, then begins to wane as it nears the Sun.*

Galileo published his findings, and his controversial conclusions supporting the Copernican theory, in 1610, in a book called *Sidereus Nuncius* (*The Starry Messenger*). In reporting these wondrous observations made with his new telescope, Galileo was directly challenging the scientific establishment and religious dogma of the time. He was (literally) playing with fire—he must certainly have been aware that only a few years earlier, in 1600, the astronomer Giordano Bruno had been burned at the stake in Rome for his heretical teaching that Earth orbited the Sun. However, by all accounts, Galileo delighted in publicly ridiculing and irritating his Aristotelian colleagues. In 1616 his ideas were judged heretical, Copernicus's works were banned by the Roman Church, and Galileo was instructed to abandon his cosmological pursuits.

But Galileo would not desist. In 1632 he raised the stakes by publishing *Dialogue Concerning the Two Chief World Systems*, which compared the Ptolemaic and Copernican models. The book presented a discussion among three people: one of them a dull-witted Aristotelian, whose views time and again were roundly defeated by the arguments of one of his two companions, an articulate proponent of the heliocentric system. To make the book accessible to a wide popular audience, Galileo wrote it in Italian rather than Latin. These actions brought Galileo into direct conflict with the Church. Eventually, the Inquisition forced him, under threat of torture, to retract his claim that Earth orbits the Sun, and he was placed under house arrest in 1633; he remained imprisoned for the rest of his life. Not until 1992 were Galileo's "crimes" publicly forgiven by the Church. But the damage to the orthodox view of the universe was done, and the Copernican genie was out of the bottle once and for all.

THE ASCENDANCY OF THE COPERNICAN SYSTEM

Although Renaissance scholars were correct, none of them could prove that our planetary system is centered on the Sun, or even that Earth moves through space. Direct evidence for this was obtained only in the early eighteenth century, when astronomers discovered the *aberration of starlight*—a slight (20") shift in the observed direction to a star, caused by Earth's motion perpendicular to the line of sight. Additional proof came in the mid-nineteenth century, with the first unambiguous measurement of stellar parallax. Further verification of the heliocentricity of the solar system came gradually, with innumerable observational tests that culminated with the expeditions of our unmanned space probes of the 1960s, 1970s, and 1980s. The development and eventual acceptance of the heliocentric model were milestones in human thinking. This removal of Earth from any position of great cosmic significance is generally known, even today, by the term *Copernican principle*.

The Copernican episode is a good example of how the scientific method, though affected at any given time by the subjective whims, human biases, and even sheer luck of researchers, does ultimately lead to a definite degree of objectivity. Over time, many groups of scientists checking, confirming, and refining experimental tests can neutralize the subjective attitudes of individuals. Usually one generation of scientists can bring sufficient objectivity to bear on a problem, though some especially revolutionary concepts are so swamped by tradition, religion, and politics that more time is necessary. In the case of heliocentricity, objective confirmation was not obtained until about three centuries after Copernicus published his work and more than 2000 years after Aristarchus had proposed the concept. Nonetheless, that objectivity *did in fact* eventually prevail.

INTERLUDE 2-2 The Scientific Method

Most ancient philosophers held firmly to the belief that, whatever the reasons for the motions of the heavens, Earth in general and humankind in particular were absolutely central to the workings of the universe. Modern science, by contrast, has arrived at a diametrically opposite view. Our present-day outlook is that Earth, the solar system, and (some would argue) humanity are ordinary in every way. This idea is often (and only half-jokingly) called the "principle of mediocrity," and it is deeply embedded in modern scientific thought. It is a natural extension of the Copernican principle discussed in Sections 2.3 and 2.4 (see also *Interlude 2-1*). Nowadays, any theory or observation that even appears to single out Earth, the solar system, or the Milky Way Galaxy as in some way special is immediately regarded with great suspicion in scientific circles.

The principle of mediocrity extends far beyond mere philosophical preference, however. Simply put, if we do not make this assumption, then we cannot make much headway in science, and we cannot do astronomy at all. Virtually every statement made in this text rests squarely on the premise that the laws of physics, as we know them here on Earth, apply everywhere else too, without modification and without exception.

This transformation in the perception of humanity's place in the universe went hand in hand with a gradual—but radical—shift in the way philosophers and scientists conducted their investigation of the cosmos. The earliest known models of the universe were based largely on imagination and pure reasoning, with little attempt to explain the workings of the heavens in terms of known earthly experience. However, history shows that some philosophers did come to realize the importance of careful observation and testing to the formulation of their theories. The success of their approach changed, slowly but surely, the way science was done and opened the door to a fuller understanding of nature.

As knowledge from all sources was sought and embraced for its own sake, the influence of logic and reasoned argument grew, and the power of myth diminished. People began to inquire more critically about themselves and the universe. They realized that thinking about nature was no longer sufficient; looking at it was also necessary. Experiments and observations became a central part of the process of inquiry. To be effective, a theory—the framework of ideas and assumptions used to explain some set of observations and make predictions about the real world—must be continually tested. If experiments and observations favor it, a theory can be further developed and refined, but if they do not, it must be rejected, no matter how appealing it originally seemed. The process is illustrated schematically in the accompanying figure. This new approach to investigation, combining thinking and doing—that is, theory and experiment—is often known as the *scientific method.* It lies at the heart of modern science.

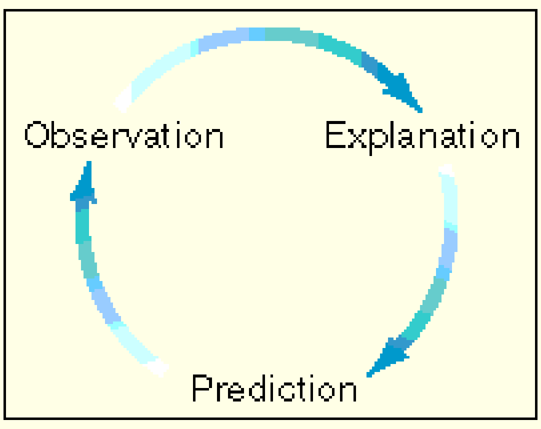
Notice, incidentally, that there is no "end point" to the process depicted in the figure. A theory can be invalidated by a single wrong prediction, but no amount of observation or experimentation can ever prove it correct. Theories simply become more and more widely accepted as their predictions are repeatedly confirmed.

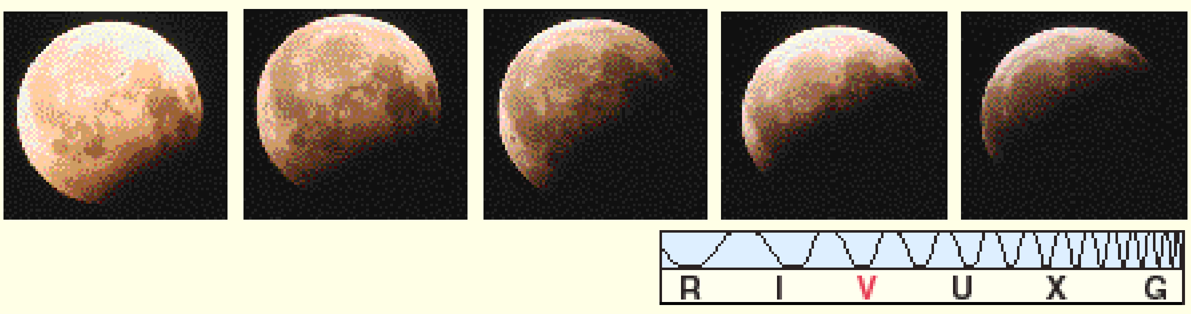
In astronomy we are rarely afforded the luxury of performing experiments to test our theories, so observation becomes vitally important. One of the first documented uses of the scientific method in an astronomical context was performed by Aristotle nearly 25 centuries ago. He noticed that during a lunar eclipse, when Earth is positioned between the Sun and the Moon, it casts a curved shadow onto the surface of the Moon. The following figure shows a series of photographs taken during a recent lunar eclipse. The Earth's shadow, projected onto the Moon's surface, is indeed slightly curved. This is what Aristotle must have seen and recorded so long ago.

Because the observed shadow seemed always to be an arc of the same circle, Aristotle concluded that Earth, the cause of the shadow, must be round. On the basis of this hypothesis—this possible explanation of the observed facts—he then went on to predict that any and all future lunar eclipses would show that Earth's shadow was curved, regardless of the orientation of our planet. That prediction has been tested every time a lunar eclipse has occurred. It has yet to be proved wrong. Aristotle was not the first person to argue that Earth is round, but he was apparently the first to offer a proof of it using the lunar-eclipse method.

The reasoning procedure Aristotle used forms the basis of all scientific inquiry today. He first made an observation. He then formulated a hypothesis to explain that observation. Finally, he tested the validity of his hypothesis by making predictions that could be confirmed or refuted by further observations. Observation, theory, and testing—these are the cornerstones of the scientific method, a technique whose power will be demonstrated again and again throughout our text.

Scientists throughout the world today use an approach that relies heavily on testing ideas. They gather data, form a working hypothesis that explains the data, and then proceed to test its predictions using experiment and observation. Experiment and observation are integral parts of the process of scientific inquiry. Theories unsupported by such evidence rarely gain any measure of acceptance in scientific circles. Used properly over a period of time, this rational, methodical approach enables us to arrive at conclusions that are mostly free of the personal bias and human values of any one scientist. The scientific method is designed to yield an objective view of the universe we inhabit.





2.6 The Dimensions of the Solar System

Kepler's laws allow us to construct a scale model of the solar system, with the correct shapes and *relative* sizes of all the planetary orbits, but they do not tell us the *actual* size of any orbit. We can express the distance to each planet only in terms of the distance from Earth to the Sun. Why is this? Because Kepler's triangulation measurements all used a portion of Earth's orbit as a baseline, distances could be expressed only relative to the size of that orbit, which was not itself determined. Thus our model of the solar system would be analogous to a road map of the United States showing the *relative* positions of cities and towns but lacking the all-important scale marker indicating distances in kilometers or miles. For example, we would know that Kansas City is about three times more distant from New York than it is from Chicago, but we would not know the actual mileage between any two points on the map.

If we could somehow determine the value of the astronomical unit—in kilometers, say—we would be able to add the vital scale marker to our map of the solar system and compute the exact distances between the Sun and each of the planets. We might propose using triangulation to measure the distance from Earth to the Sun directly. However, we would find it impossible to measure the Sun's parallax using Earth's diameter as a baseline. The Sun is too bright, too big, and too fuzzy for us to distinguish any apparent displacement relative to a field of distant stars. To measure the Sun's distance from Earth, we must resort to some other method.

Before the middle of the twentieth century, the most accurate measurements of the astronomical unit were made using triangulation on the planets Mercury and Venus during their rare *transits* of the Sun—that is, during the brief periods when those planets passed directly between the Sun and Earth (as shown for the case of Mercury in Figure 2.15). Because the time at which a transit occurs can be determined with great precision, astronomers can use this information to make very accurate measurements of a planet's position in the sky. They can then use simple geometry to compute the distance to the planet by combining observations made from different locations on Earth, as discussed earlier in Chapter 1. (Sec. 1.5) For example, the parallax of Venus at closest approach to Earth, as seen from two diametrically opposite points on Earth (separated by about 13,000 km), is about 1 arc minute—at the limit of naked-eye capabilities but easily measurable telescopically. This parallax represents a distance of 45 million km.

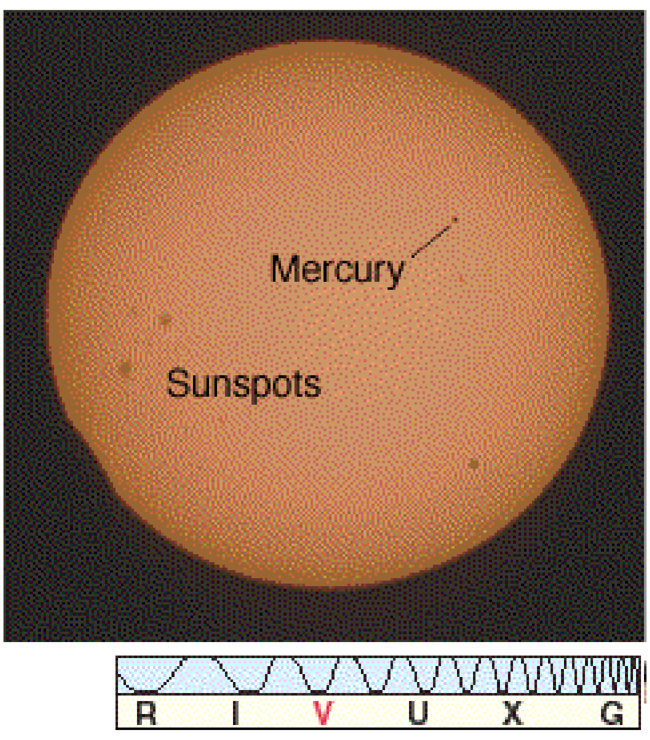


Figure 2.15 A solar transit of Mercury. Such transits happen only about once per decade, because Mercury's orbit does not quite coincide with the plane of the ecliptic. Transits of Venus are even rarer, occurring only about twice per century.

Knowing the distance to Venus, we can compute the magnitude of the astronomical unit. Figure 2.16 is an idealized diagram of the Sun—Earth—Venus orbital geometry. The planetary orbits are drawn as circles here, but in reality they are slight ellipses. This is a subtle difference, and we can correct for it using detailed knowledge of orbital motions. Assuming for the sake of simplicity that the orbits are perfect circles, we see from the figure that the distance from Earth to Venus at closest approach is approximately 0.3 A.U. Knowing that 0.3 A.U. is 45,000,000 km makes determining 1 A.U. straightforward—the answer is 45,000,000/0.3, or 150,000,000 km.

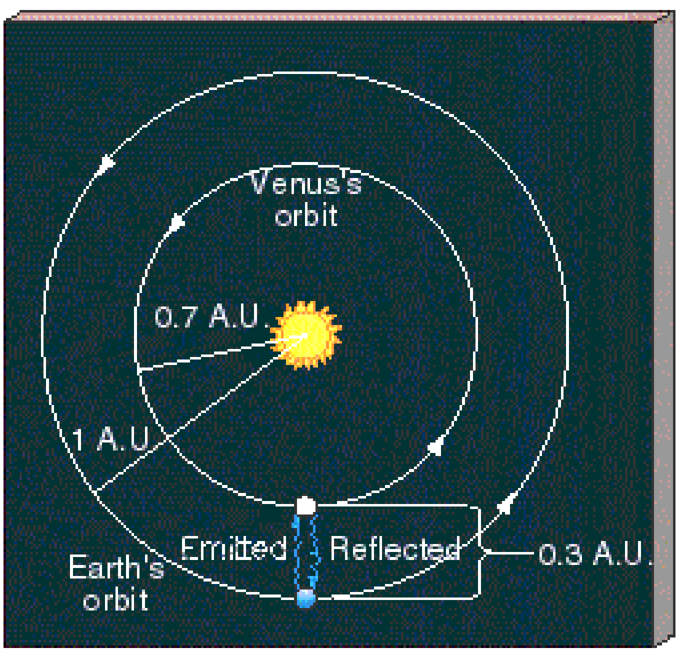


Figure 2.16 Simplified geometry of the orbits of Earth and Venus as they move around the Sun. The wavy lines represent the paths along which radar signals might be transmitted toward Venus and received back at Earth at the moment when Venus is at its minimum distance from Earth. Because the radius of Earth's orbit is 1 A.U. and that of Venus is about 0.7 A.U., we know that this distance is 0.3 A.U. Thus, radar measurements allow us to determine the astronomical unit in kilometers.

The modern method for deriving the absolute scale of the solar system uses radar rather than triangulation. The word **radar** is an acronym for **ra**dio **d**etection **a**nd **r**anging. In this technique, radio waves are transmitted toward an astronomical body, such as a planet. (We cannot use radar ranging to measure the distance to the Sun directly because radio signals are absorbed at the solar surface and are not reflected to Earth.) The returning echo indicates the body's direction and range, or distance, in absolute terms—that is, in kilometers rather than in astronomical units. Multiplying the round-trip travel time of the radar signal (the time elapsed between transmission of the signal and reception of the echo) by the speed of light (300,000 km/s, which is also the speed of radio waves), we obtain twice the distance to the target planet.

Venus, whose orbit periodically brings it closest to Earth, is the most common target for radar ranging. The round-trip travel time (for example, at closest approach, as indicated by the wavy lines on Figure 2.16) can be measured with high precision—in fact, well enough to determine the planet's distance to an accuracy of about 1 km. In this way, the astronomical unit is now known to be 149,597,870 km. We will use the rounded-off value of 1.5×10^8 km in this text. (For more on the use of scientific notation to represent very large or very small numbers, see Appendix 1.)

Having determined the value of the astronomical unit, we can reexpress the sizes of the other planetary orbits in terms of more familiar units, such as miles or kilometers. The entire scale of the solar system can then be calibrated to high precision.

2.7 Newton's Laws

7 Kepler's three laws, which so simplified the solar system, were discovered *empirically*. In other words, they resulted solely from the analysis of observational data and were not derived from any theory or mathematical model. Indeed, Kepler did not have any appreciation for the physics underlying his laws. Nor did Copernicus understand the basic reasons *why* his heliocentric model of the solar system worked. Even Galileo, often called the father of modern physics, failed to understand why the planets orbit the Sun.

What prevents the planets from flying off into space or from falling into the Sun? What causes them to revolve about the Sun, apparently endlessly? To be sure, the motions of the planets obey Kepler's three laws, but only by considering something more fundamental than those laws can we really understand these motions. The heliocentric system was secured when, in the seventeenth century, the British mathematician Isaac Newton (Figure 2.17) developed a deeper understanding of the way *all* objects move and interact with one another as they do.

Figure 2.17 Sir Isaac Newton (1642—1727).

THE LAWS OF MOTION

Isaac Newton was born in Lincolnshire, England, on Christmas Day in 1642, the year that Galileo died. Newton studied at Trinity College of Cambridge University, but when the bubonic plague reached Cambridge in 1665, he returned to the relative safety of his home for 2 years. During that time he made probably the most famous of his discoveries, the law of gravity (although it is but one of the many major scientific advances Newton is responsible for). However, either because he regarded the theory as incomplete or possibly because he was afraid that he would be attacked or plagiarized by his colleagues, he did not tell anyone of his monumental achievement for almost 20 years. It was not until 1684, when Newton was discussing with Edmund Halley (of Halley's comet fame) the leading astronomical problem of the day—*Why* do the planets move according to Kepler's laws?—that he astounded his companion by revealing that he had solved the problem in its entirety nearly two decades before!

Prompted by Halley, Newton published his theories in perhaps the most influential physics book ever written: *Philosophiae Naturalis Principia Mathematica (The Mathematical Principles of Natural Philosophy*—what we would today call "science"), usually known simply as Newton's *Principia*. The ideas expressed in that work form the basis for what is now known as **Newtonian mechanics**. Three basic laws of motion, the law of gravity, and a little calculus (which Newton also invented) are sufficient to explain and quantify virtually all the complex dynamic behavior we see on Earth and throughout the universe. Newton's laws are listed in *More Precisely 2-2.*

Figure 2.18 illustrates *Newton's first law of motion*. The first law simply states that a moving object will move forever in a straight line unless some external **force** changes its direction of motion. For example, the object might glance off a brick wall or be hit with a baseball bat; in either case, a force changes the original motion of the object. The tendency of an object to keep moving at the same speed and in the same direction unless acted upon by a force is known as **inertia**. A familiar measure of an object's inertia is its **mass**—loosely speaking, the total amount of matter it contains. The greater an object's mass, the more inertia it has, and the greater is the force needed to change its state of motion.

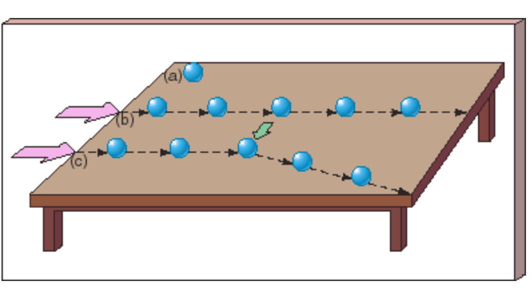


Figure 2.18 An object at rest will remain at rest (a) until some force acts on it (b). It will then remain in that state of uniform motion until another force acts on it. The arrow in (c) shows a second force acting at a direction different from the first, which causes the object to change its direction of motion.

Newton's first law contrasts sharply with the view of Aristotle, who maintained (incorrectly) that the natural state of an object was to be *at rest*—most probably an opinion based on Aristotle's observations of the effect of friction. In our discussion we will neglect friction—the force that slows balls rolling along the ground, blocks sliding across tabletops, and baseballs moving through the air. In any case, it is not an issue for the planets because there is no appreciable friction in outer space. The fallacy in Aristotle's argument was first realized and exposed by Galileo, who conceived of the notion of inertia long before Newton formalized it into a law.

The rate of change of the velocity of an object—speeding up, slowing down, or simply changing direction—is called its **acceleration**. *Newton's second law* states that the acceleration of an object is directly proportional to the applied force and inversely proportional to its mass—that is, the greater the force acting on the object, or the smaller the mass of the object, the greater its acceleration. Thus, if two objects are pulled with the same force, the more massive one will accelerate less; if two identical objects are pulled with different forces, the one experiencing the greater force will accelerate more.

Finally, *Newton's third law* simply tells us that forces cannot occur in isolation—if body A exerts a force on body B, then body B necessarily exerts a force on body A that is equal in magnitude, but oppositely directed.

Only in extreme circumstances do Newton's laws break down, and this fact was not realized until the twentieth century, when Albert Einstein's theories of relativity once again revolutionized our view of the universe (see Chapter 22). Most of the time, however, Newtonian mechanics provides an excellent description of the motion of planets, stars, and galaxies through the cosmos.

GRAVITY

Forces can act *instantaneously* or *continuously*. To a good approximation, the force from a baseball bat that hits a home run can be thought of as being instantaneous in nature. A good example of a continuous force is the one that prevents the baseball from zooming off into space—**gravity**, the phenomenon that started Newton on the path to the discovery of his laws. Newton hypothesized that any object having mass always exerts an attractive *gravitational force* on all other massive objects. The more massive an object, the stronger its gravitational pull.

Consider a baseball thrown upward from Earth's surface, as illustrated in Figure 2.19. In accordance with Newton's first law, the downward force of Earth's gravity continuously modifies the baseball's velocity, slowing the initial upward motion and eventually causing the ball to fall back to the ground. Of course, the baseball, having some mass of its own, also exerts a gravitational pull on Earth. By Newton's third law, this force is equal and opposite to the weight of the ball (the force with which Earth attracts it). But, by Newton's second law, Earth has a much greater effect on the light baseball than the baseball has on the much more massive Earth. The ball and Earth feel the same gravitational force, but Earth's *acceleration* is much smaller.

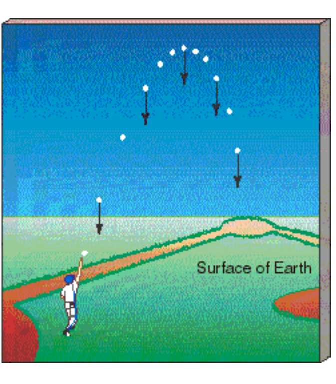
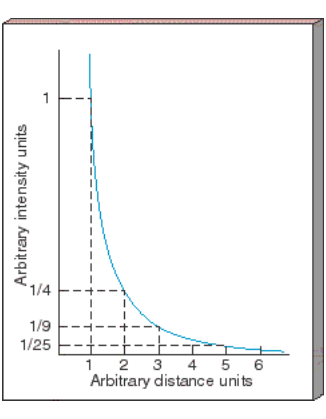


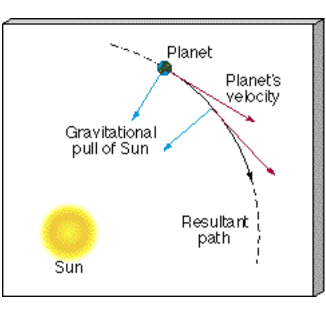
Figure 2.19 A ball thrown up from the surface of a massive object such as a planet is pulled continuously by the gravity of that planet (and, conversely, the gravity of the ball continuously pulls the planet).

Now consider the trajectory of the same baseball batted from the surface of the Moon. The pull of gravity is about one-sixth as great on the Moon as on Earth, so the baseball's velocity changes more slowly—a typical home run in a ballpark on Earth would travel nearly half a mile on the Moon. The Moon, less massive than Earth, has less gravitational influence on the baseball. The magnitude of the gravitational force, then, depends on the *masses* of the attracting bodies. Theoretical insight, as well as delicate laboratory experiments, tells us that the force is in fact directly proportional to the product of the two masses.

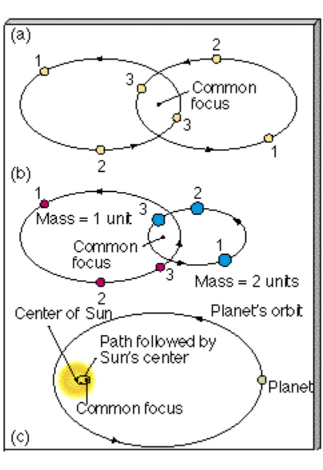
Studying the motions of the planets reveals a second aspect of the gravitational force. At locations equidistant from the Sun's center, the gravitational force has the same strength, and it is always directed toward the Sun. Furthermore, detailed calculation of the planets' accelerations as they orbit the Sun reveals that the strength of the Sun's gravitational pull decreases in proportion to the *square* of the distance from the Sun. (Newton himself is said to have first realized this fact by comparing the accelerations not of the planets but of the Moon and an apple falling to the ground—the basic reasoning is the same in either case.) The force of gravity is said to obey an **inverse-square law**. As shown in Figure 2.20, inverse-square forces decrease rapidly with distance from their source. For example, tripling the distance makes the force $3^2 = 9$ times weaker, while multiplying the distance by 5 results in a force that is $5^2 = 25$ times weaker. Despite this rapid decrease, the force never quite reaches zero. The gravitational pull of an object having some mass can never be completely extinguished.



[illegible]



[illegible]



[illegible] *their mutual gravity, are identical ellipses with a common focus. That focus is not at the center of either star but instead is located at the center of mass of the pair, midway between them. The positions of the two bodies at three different times are indicated by the pairs of numbers. (Notice that a line joining the bodies always passes through the common focus.) (b) The orbits of two bodies, one of which is twice as massive as the other. Again, the elliptical orbits have a common focus, and the two ellipses have the same eccentricity. However, in accordance with Newton's laws of motion, the more massive body moves more slowly, and in a smaller orbit, staying closer to the center of mass (at the common focus). In this particular case, the larger ellipse is twice the size of the smaller one. (c) In this extreme case of a hypothetical planet orbiting the Sun, the common focus of the two orbits lies inside the Sun.*

The change to Kepler's third law is also small in the case of a planet orbiting the Sun but very important in other circumstances, such as the orbital motion of two stars that are gravitationally bound to each other. Following through the mathematics of Newton's theory, we find that the true relationship between the semi-major axis a (measured in astronomical units) of the planet's orbit relative to the Sun and its orbital period *P* (in Earth years) is

$$P^2 \text{ (in Earth years)} = \frac{a^3 \text{ (in astronomical units)}}{M_{\text{total}} \text{ (in solar masses)}}$$

where M_{total} is the *combined* mass of the two objects. Notice that Newton's restatement of Kepler's third law preserves the proportionality between P^2 and a^3, but now the proportionality includes M_{total}, so it is *not* quite the same for all the planets. The Sun's mass is so great, however, that the differences in M_{total} among the various combinations of the Sun and the other planets are almost unnoticeable, and so Kepler's third law, as originally stated, is a very good approximation. This modified form of Kepler's third law is true in all circumstances, inside or outside the solar system.

ESCAPING FOREVER

The law of gravity that describes the orbits of planets around the Sun applies equally well to natural moons and artificial satellites orbiting any planet. All our Earth-orbiting, human-made satellites move along paths governed by a combination of the inward pull of Earth's gravity and the forward motion gained during the rocket launch. If the rocket initially imparts enough speed to the satellite, it can go into orbit. Satellites not given enough speed at launch (such as intercontinental ballistic missiles, ICBMs) fail to achieve orbit and fall back to Earth (Figure 2.23). (Technically, ICBMs actually do orbit Earth's attracting center, but their orbits intersect Earth's surface.)

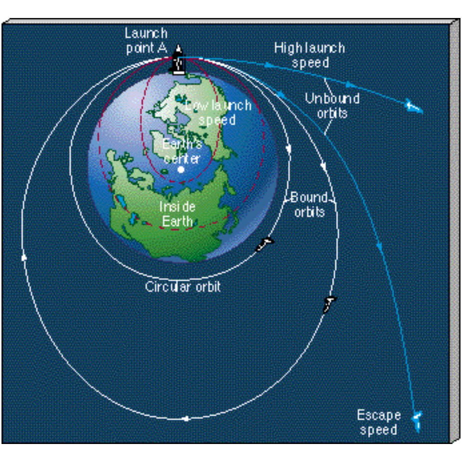


Figure 2.23 The effect of launch speed on the trajectory of a satellite. With too low a speed at point A the satellite will simply fall back to Earth. Given enough speed, however, the satellite will go into orbit — it "falls around Earth." As the initial speed at point A is increased, the orbit will become more and more elongated. When the initial speed exceeds the escape speed, the satellite will become unbound from Earth and will escape along a hyperbolic trajectory.

Some space vehicles, such as the robot probes that visit the other planets, attain enough speed to escape our planet's gravitational field and move away from Earth forever. This speed, known as the **escape speed**, is about 41 percent greater (actually, (check)2 = 1.414...times greater) than the speed of a circular orbit at any given radius.*

**In terms of the formula presented earlier (see More Precisely 2-3), the escape speed is given by*

$$v_{\text{escape}} = \sqrt{\frac{2Gm}{r}}.$$

At less than escape speed, the adage "what goes up must come down" (or at least stay in orbit) still applies. At more than the escape speed, however, a spacecraft will leave Earth for good (neglecting the effect of air resistance on its way through Earth's atmosphere and assuming that we don't turn the craft around using an on-board rocket motor). Planets, stars, galaxies—all gravitating bodies—have escape speeds. No matter how massive the body, gravity decreases with distance. As a result, the escape speed diminishes with increasing separation. The farther we go from Earth (or any gravitating body), the easier it becomes to escape.

The speed of a satellite in a circular orbit just above Earth's atmosphere is 7.9 km/s (roughly 18,000 mph). The satellite would have to travel at 11.2 km/s (about 25,000 mph) to escape from Earth altogether. If an object exceeds the escape speed, its motion is said to be **unbound**, and the orbit is no longer an ellipse. In fact, the path of the spacecraft relative to Earth is a related geometric figure called a *hyperbola*. If we simply change the word *ellipse* to *hyperbola*, the modified version of Kepler's first law still applies, as does Kepler's second law. (Kepler's third law does not extend to unbound orbits because it doesn't make sense to talk about a period in those cases.)

Newton's laws explain the paths of objects moving at any point in space near any gravitating body. These laws provide a firm physical and mathematical foundation for Copernicus's heliocentric model of the solar system and for Kepler's laws of planetary motions. But they do much more than that. Newtonian gravitation governs not only the planets, moons, and satellites in their elliptical orbits but also the stars and galaxies in their motion throughout our universe—as well as apples falling to the ground.

MORE PRECISELY 2-2 Newton's Laws of Motion and Gravitation

1. Every body continues in a state of rest or in a state of uniform motion in a straight line unless it is compelled to change that state by a force acting on it.

It requires no force to maintain motion in a straight line with constant velocity—that is, motion with constant speed and constant direction in space. The tendency of a body to remain in a state of uniform motion is usually called inertia. When velocity does vary (the speed increases or decreases, or the direction of motion changes), its rate of change is called acceleration. The relation of acceleration to any forces acting on a body is the subject of the second law of motion:

2. When a force *F* acts on a body of mass *m*, it produces in it an acceleration *a* equal to the force divided by the mass. Thus, a = F/m, or F = ma.

In honor of Newton, the SI unit of force is named after him. By definition, 1 newton (N) is the force required to cause a mass of 1 kilogram to accelerate at a rate of 1 meter per second every second. Newton's third law relates the forces acting between separate bodies:

3. To every action there is an equal and opposite reaction.

This law means, for example, that you attract Earth with exactly the same force as it attracts you (a force known as your weight). This attraction is governed by one final law:

The Law of Universal Gravitation ("Newton's Law of Gravity")

Every particle of matter in the universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them. In other words, two bodies of masses m_1 and m_2, separated by a distance r, attract each other with a force F that is proportional to $(m_1 \times m_2)/r^2$. The constant of proportionality is known as the gravitational constant, or often simply as Newton's constant, and is always denoted by the letter *G*. We can then express the law of gravity as

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

The value of *G* has been measured in extremely delicate laboratory experiments. In SI units, its value is 6.67×10^{-11} newton meter^2/kilogram^2 (N m5%* ú ø ý = ; % ü ¬ û ÿ =

MORE PRECISELY 2-3 Weighing the Sun

We can use Newtonian mechanics to calculate the relationship between the distance *(r)* and the speed *(v)* of a planet moving in a circular orbit around the Sun (of mass *m*). By calculating the force required to keep the planet moving in a circle and comparing it with the gravitational force due to the Sun, it can be shown that the circular speed is

$$v = \sqrt{\frac{Gm}{r}},$$

where the gravitational constant G is defined in *More Precisely 2-2*. Dividing this speed into the circumference of the orbit ($2\pi r$), we obtain the modified form of Kepler's third law (equivalent to the formula presented in the text):

$$P = 2\pi\sqrt{\frac{r^3}{Gm}},$$

where $P = 2\pi r/v$ is the orbital period.

Because we have measured G in the laboratory on Earth and because we know the length of a year and the size of the astronomical unit, we can use Newtonian mechanics to *weigh* the Sun. Inserting the known values of v = 30 km/s, r = 1 A.U. = 1.5×10^{11} m, and $G = 6.7 \times 10^{-11}$ N m^2/kg^2in the equation, we can calculate the mass of the Sun to be 2.0×10^{30} kg—an enormous mass by terrestrial standards. Similarly, knowing the distance to the Moon and the length of the (sidereal) month, we can measure the mass of Earth to be 6.0×10^{24} kg.

In fact, this is how basically *all* masses are measured in astronomy. Because we can't just go out and weigh an astronomical object when we need to know its mass, we must look for its gravitational influence on something else. This principle applies to planets, stars, galaxies, and even clusters of galaxies—very different objects but all subject to the same physical laws.

Chapter Review

SUMMARY

Many ancient cultures constructed elaborate structures that served as calendars and astronomical observatories. The study of the universe on the very largest scales is called **cosmology**.

Unlike the Sun and the Moon, planets sometimes appear to temporarily reverse their direction of motion (from night to night) relative to the stars and then resume their normal "forward" course. This phenomenon is called **retrograde motion**.

Geocentric models of the universe were based on the assumption that the Sun, the Moon, and the planets all orbit Earth. The most successful and long-lived of these was the **Ptolemaic model**. To account for retrograde motion within the geocentric picture, it was necessary to suppose that planets moved on small circles called **epicycles**, whose centers orbited Earth on larger circles called **deferents**. The **heliocentric** view of the solar system holds that Earth, like all the planets, orbits the Sun. This model accounts for retrograde motion and the observed size and brightness variations of the planets in a much more natural way than the geocentric model. The widespread realization during the Renaissance that the solar system is Sun centered, and not Earth centered, is known as the **Copernican revolution**, in honor of Nicholas Copernicus, who laid the foundations of the modern heliocentric model.

Johannes Kepler improved on Copernicus's model with his three **laws of planetary motion**: (1) Planetary orbits are **ellipses**, with the Sun at one **focus**. (2) A planet moves faster as its orbit takes it closer to the Sun. (3) The **semi-major axis** of the orbit is related in a simple way to the planet's orbit **period**. Most planets move on orbits whose **eccentricities** are quite small, so their paths differ only slightly from perfect circles.

Galileo Galilei is often regarded as the father of experimental science. His telescopic observations of the Moon, the Sun, Venus, and Jupiter played a crucial role in supporting and strengthening the Copernican picture of the solar system.

The distance from Earth to the Sun is called the **astronomical unit**. Nowadays, the astronomical unit is determined by bouncing **radar** signals off the planet Venus and measuring the time taken for the signal to return.

Isaac Newton succeeded in explaining Kepler's laws in terms of a few general physical principles, now known as **Newtonian mechanics**. The tendency of a body to keep moving at constant velocity is called **inertia**. The greater the body's **mass**, the greater its inertia. To change the velocity, a **force** must be applied. The rate of change of velocity, called **acceleration**, is equal to the applied force divided by the body's mass. To explain planetary orbits, Newton postulated that **gravity** attracts the planets to the Sun. Every object with any mass is surrounded by a **gravitational field**, whose strength decreases with distance according to an **inverse-square law**. This field determines the gravitational force exerted by the object on any other body in the universe.

Newton's laws imply that a planet does not orbit the precise center of the Sun but instead that both the planet and the Sun orbit the common **center of mass** of the two bodies.

For an object to escape from the gravitational pull of another, its speed must exceed the **escape speed** of the second body. In this case, the motion is said to be **unbound**, and the orbital path is no longer an ellipse, although it is still described by Newton's laws.

SELF-TEST: TRUE OR FALSE?

1. Historical records show that it was Aristotle who first proposed that all planets revolve around the Sun. HINT

2. The teachings of Aristotle remained unchallenged until the eighteenth century a.d. HINT

3. Ptolemy was responsible for a geocentric model that was successful at predicting the positions of the planets, Moon, and the Sun. HINT

4. The heliocentric model of the universe held that Earth was at the center, and everything else moved around it. HINT

5. Kepler's discoveries regarding the orbital motion of the planets were based on his own observations. HINT

6. The Sun's location in a planet's orbit is at the center. HINT

7. The semi-major axis of an orbit is half the major axis. HINT

8. A circle has an eccentricity of zero. HINT

9. The astronomical unit is a distance equal to the semi-major axis of Earth's orbit around the Sun. HINT

10. The speed of a planet orbiting the Sun is independent of the planet's position in its orbit. HINT

11. Kepler's laws work for only the six planets known in his time. HINT

12. Kepler never knew the true distances between the planets and the Sun, only their relative distances. HINT

13. Galileo's observations of the sky were made with the naked eye. HINT

14. Using his laws of motion and gravity, Newton was able to prove Kepler's laws. HINT

15. You throw a baseball to someone. Before the ball is caught, it is temporarily in orbit around Earth's center.

SELF-TEST: FILL IN THE BLANK

1. Stonehenge was used as a _____ by people in the Stone Age. HINT

2. Accurate records of comets and "guest" stars were kept over many centuries by _____ astrologers. HINT

3. The astronomical knowledge of ancient Greece was kept alive and augmented by _____ astronomers. HINT

4. The apparent "backward" (westward motion) of the planets Mars, Jupiter, or Saturn in the sky relative to the stars is known as _____ motion. HINT

5. Observation, theory, and testing are the cornerstones of the _____. HINT

6. The heliocentric model was reinvented by _____. HINT

7. Central to the heliocentric model is the assertion that the observed motions of the planets and the Sun are the result of _____ motion around the Sun. HINT

8. Kepler's laws were based on observational data obtained by _____. HINT

9. Kepler discovered that the shape of an orbit is an _____, not a _____, as had previously been believed. HINT

10. Kepler's third law relates the _____ of the orbital period to the _____ of the semi-major axis. HINT

11. Galileo discovered _____ orbiting Jupiter, the _____ of Venus, and the Sun's rotation from observations of _____. HINT

12. The modern method of measuring the astronomical unit uses _____ measurements of a planet or asteroid. HINT

13. Newton's first law states that a moving object will continue to move in a straight line with constant speed unless acted upon by a _____. HINT

14. Newton's law of gravity states that the gravitational force between two objects depends on the _____ of their masses and inversely on the _____ of their separation.

15. Newton discovered that, in Kepler's third law, the orbital period depends on the semi-major axis and on the sum of the _____ of the two objects involved. HINT

REVIEW AND DISCUSSION

1. What contributions to modern astronomy were made by Chinese and Islamic astronomers during the Dark Ages of medieval Europe? HINT

2. Briefly describe the geocentric model of the universe. HINT

3. The benefit of our current knowledge lets us see flaws in the Ptolemaic model of the universe. What is its basic flaw? HINT

4. What was the great contribution of Copernicus to our knowledge of the solar system? What was still a flaw in the Copernican model? HINT

5. When were Copernicus's ideas finally accepted? HINT

6. What is the Copernican principle? HINT

7. What discoveries of Galileo helped confirm the views of Copernicus? HINT

8. Briefly describe Kepler's three laws of orbital motion. HINT

9. If radio waves cannot be reflected from the Sun, how can radar be used to find the distance from Earth to the Sun? HINT

10. What is meant by the statement that Kepler's laws are empirical in nature? HINT

11. List the two modifications made by Newton to Kepler's laws. HINT

12. Why does a baseball fall toward Earth and not Earth toward the baseball? HINT

13. Why would a baseball go higher if it were thrown up from the surface of the Moon than if it were thrown with the same velocity from the surface of Earth? HINT

14. What is the meaning of the term escape speed? HINT

15. What would happen to Earth if the Sun's gravity were suddenly "turned off?" HINT

PROBLEMS

1. Tycho Brahe's observations of the stars and planets were accurate to about 1 arc minute (1'). To what distance does this angle correspond (a) at the distance of the Moon, (b) of the Sun, (c) of Saturn (at closest approach)?

2. Assume for simplicity that Earth and Mars move on circular orbits of radii 1.0 A.U. and 1.5 A.U., respectively, in exactly the same plane. To an observer on Earth, through what angle will Mars appear to move relative to the stars over the course of 24 hours, when the two planets are at closest approach? Will the apparent motion be prograde or retrograde? HINT

3. Using the data in Table 2.1 show that Pluto is closer to the Sun at perihelion (the point of closest approach to the Sun in its orbit) than Neptune is at any point in its orbit. For simplicity, you may assume that Neptune has a circular orbit, which is not far from the truth.

4. An asteroid has a perihelion distance of 2.0 A.U. and an aphelion distance of 4.0 A.U. Calculate its orbital semi-major axis, eccentricity, and period.

5. Halley's comet has a perihelion distance of 0.6 A.U. and an orbital period of 76 years. What is its aphelion distance from the Sun?

6. How long will a radar signal take to complete a round trip between Earth and Mars when the two planets are 0.7 A.U. apart? HINT

7. Jupiter's moon Callisto orbits the planet at a distance of 1.88 million km. Callisto's orbital period about Jupiter is 16.7 days. What is the mass of Jupiter? [Assume that Callisto's mass is negligible compared with that of Jupiter, and use the modified version of Kepler's third law (Section 2.7).] HINT

8. The acceleration due to gravity at Earth's surface is 9.80 m/s^2. What is the acceleration at altitudes of (a) 100 km? (b) 1000 km? (c) 10,000 km? HINT

9. Use Newton's law of gravity to calculate the force of gravity between you and Earth. Convert your answer, which will be in newtons, to pounds using the conversion 4.45 N equals 1 pound. What do you normally call this force? HINT

10. The Moon's mass is 7.35×10^{22} kg and its radius is 1700 km. What is the speed of a spacecraft moving in a circular orbit just above the lunar surface? What is the escape speed from the Moon? HINT

PROJECTS

1. Look in an almanac for the date of opposition of one or all of these bright planets: Mars, Jupiter, and Saturn. At opposition, these planets are at their closest points to Earth and are at their largest and brightest in the night sky. Observe these planets. How long before opposition does each planet's retrograde motion begin? How long afterward does it end?

2. Draw an ellipse. (See Figure 2.11) You'll need two pins, a piece of string, and a pencil. Tie the string in a loop and place it around the pins. Place the pencil inside the loop and run it around the inside of the string, holding the loop taut. The two pins will be at the foci of the ellipse. What is the eccentricity of the ellipse you have drawn?

3. Use a small telescope to replicate Galileo's observations of Jupiter's four largest moons. Note the moons' brightnesses and their locations with respect to Jupiter. If you watch over a period of several nights, draw what you see; you'll notice that these moons change their positions as they orbit the giant planet. Check the charts given monthly in *Astronomy or Sky & Telescope* magazines to identify each moon you see.

PREVIOUS

C

C ring One of three Saturnian rings visible from Earth. The C ring lies closest to the planet and is relatively thin compared to the A and B rings.

carbon-detonation supernova See type-I supernova.

Cassegrain telescope A type of reflecting telescope in which incoming light hits the primary mirror and is then reflected upward toward the prime focus, where a secondary mirror reflects the light back down through a small hole in the main mirror, into a detector or eyepiece.

Cassini Division A relatively empty gap in Saturn's ring system between the A and B rings, discovered in 1675 by Giovanni Cassini. It is now known to contain a number of thin ringlets.

catastrophic theory A theory that invokes statistically unlikely accidental events to account for observations.

celestial&151;coordinates Pair of quantities—right ascension and declination—similar to longitude and latitude on Earth, used to pinpoint locations of objects on the celestial sphere.

celestial equator The projection of the Earth's equator onto the celestial sphere.

celestial sphere Imaginary sphere surrounding the Earth, to which all objects in the sky were once considered to be attached.

center of mass The "average" position in space of a collection of massive bodies, taking their masses into account. In an isolated system this point moves with constant velocity, according to Newtonian mechanics.

Cepheid variable Star whose luminosity varies in a characteristic way, with a rapid rise in brightness followed by a slower decline. The period of a Cepheid variable star is related to its luminosity, so a determination of this period can be used to obtain an estimate of the star's distance.

chaotic rotation Unpredictable tumbling motion that non-spherical bodies in eccentric orbits, such as Saturn's satellite Hyperion, can exhibit. No amount of observation of an object rotating chaotically will ever show a well-defined period.

charge-coupled device (CCD) Electronic device used for data acquisition, composed of many tiny pixels, each of which records a buildup of charge to measure the amount of light striking it.

chromatic aberration The tendency for a lens to focus red and blue light differently, causing images to become blurred.

chromosphere The Sun's lower atmosphere, lying just above the visible photosphere.

closed universe Geometry that the universe as a whole would have if the density of matter is above the critical value. A closed universe is finite in extent, and has no edge, like the surface of a sphere. It has enough mass to stop the present expansion, and will eventually collapse.

cold dark matter Class of dark-matter candidates made up of very heavy particles, such as supersymmetric relics.

collecting area The total area of a telescope that is capable of capturing incoming radiation. The larger the telescope, the greater its collecting area, and the fainter the objects it can detect.

color index A convenient method of quantifying a star's color by comparing its apparent brightness as measured through different filters. If the star's radiation is well described by a black-body spectrum, the ratio of its blue intensity (B) to its visual intensity (V) is a measure of the object's surface temperature.

color-magnitude diagram A way of plotting stellar properties, in which absolute magnitude is plotted against color index.

coma An effect occurring during the formation of an off-axis image in a telescope. Stars whose light enters the telescope at a large angle acquire comet-like tails on their images. The brightest part of a comet, often referred to as the "head."

comet A small body, composed mainly of ice and dust, in an elliptical orbit about the Sun. As it comes close to the Sun, some of its material is vaporized to form a gaseous head and extended tail.

comparative planetology The systematic study of the similarities and differences among the planets, with the goal of obtaining deeper insight into how the solar system formed and has evolved in time.

condensation nuclei Dust grains in the interstellar medium which act as seeds around which other material can coagulate. The presence of dust was very important in causing matter to clump during the formation of the solar system.

condensation theory Currently favored model of solar system formation which combines features of the old nebular theory with new information about interstellar dust grains, which acted as condensation nuclei.

conservation of mass and energy A fundamental law of modern physics which states that the sum of mass and energy must always remain constant in any physical process. In fusion reactions, the lost mass is converted into energy, primarily in the form of electromagnetic radiation.

constellation A human grouping of stars in the night sky into a recognizable pattern.

contact binary A binary star system in which both stars have expanded to fill their Roche lobes and the surfaces of the two stars merge. The binary system now consists of two nuclear burning stellar cores surrounded by a continuous common envelope.

continuous spectrum Spectrum in which the radiation is distributed over all frequencies, not just a few specific frequency ranges. A prime example is the black-body radiation emitted by a hot, dense body.

convection Churning motion resulting from the constant upwelling of warm fluid and the concurrent downward flow of cooler material to take its place.

convection zone Region of the Sun's interior, lying just below the surface, where the material of the Sun is in constant convective motion. This region extends into the solar interior to a depth of about 200,000 km.

Copernican revolution The realization toward the end of the sixteenth century that Earth is not at the center of the universe.

core The central region of Earth, surrounded by the mantle. The central region of the Sun.

core-collapse supernova See type-II supernova.

core hydrogen burning The energy burning stage for main sequence stars, in which the helium is produced by hydrogen fusion in the central region of the star. A typical star spends up to 90% of its lifetime in hydrostatic equilibrium brought about by the balance between gravity and the energy generated by core hydrogen burning.

corona One of numerous large, roughly circular regions on the surface of Venus, thought to have been caused by upwelling mantle material causing the planet's crust to bulge outward.

corona The tenuous outer atmosphere of the Sun, which lies just above the chromosphere, and at great distances turns into the solar wind.

coronal hole Vast regions of the Sun's atmosphere where the density of matter is about 10 times lower than average. The gas there streams freely into space at high speeds, escaping the Sun completely.

cosmic distance scale Collection of indirect distance-measurement techniques that astronomers use to measure the scale of the universe.

cosmic evolution The collection of the seven major phases of the history of the universe, namely galactic, stellar, planetary, chemical, biological, cultural, and future evolution.

cosmic microwave background The almost perfectly isotropic radio signal that is the electro-magnetic remnant of the Big Bang.

cosmological principle Two assumptions which make up the basis of cosmology, namely that the universe is homogeneous and isotropic on sufficiently large scales.

cosmological redshift The component of the redshift of an object which is due only to the Hubble flow of the universe.

cosmology The study of the structure and evolution of the entire universe.

crater Bowl-shaped depression on the surface of a planet or moon, resulting from a collision with interplanetary debris.

critical density The cosmic density corresponding to the dividing line between a universe that recollapses and one that expands forever.

critical universe Geometry that the universe would have if the density of matter is exactly the critical density. The universe is infinite in extent, and has zero curvature. The expansion will continue forever, but approach an expansion speed of zero.

crust Layer of the Earth which contains the solid continents and the seafloor.

R

radar Acronym for RAdio Detection And Ranging. Radio waves are bounced off an object, and the time at which the echo is received indicates its distance.

radial motion Motion along a particular line of sight, which induces apparent changes in the wavelength (or frequency) of radiation received.

radiation A way in which energy is transferred from place to place in the form of a wave. Light is a form of electromagnetic radiation.

radiation darkening The effect of chemical reactions that result when high-energy particles strike the icy surfaces of objects in the outer solar system. The reactions lead to a build-up of a dark layer of material.

radiation-dominated universe Early epoch in the universe, when the density of radiation in the cosmos exceeded the density of matter.

radiation zone Region of the Sun's interior where extremely high temperatures guarantee that the gas is completely ionized. Photons are only occasionally diverted by electrons, and travel through this region with relative ease.

radio Region of the electromagnetic spectrum corresponding to radiation of the longest wavelengths.

radio galaxy Type of active galaxy that emits most of its energy in the form of long-wavelength radiation.

radio lobe Roundish region of radio-emitting gas, lying well beyond the center of a radio galaxy.

radio telescope Large instrument designed to detect radiation from space in radio wavelengths.

radioactivity The release of energy by rare, heavy elements when their nuclei decay into lighter nuclei.

radius-luminosity-temperature relation A mathematical proportionality, arising from simple geometry and Stefan's law, which allows astronomers to indirectly determine the radius of a star once its luminosity and temperature are known.

red dwarf Small, cool faint star at the lower-right end of the main sequence on the Hertzsprung–Russell diagram.

red giant A giant star whose surface temperature is relatively low, so that it glows with a red color.

red giant branch The section of the evolutionary track of a star corresponding to intense hydrogen shell burning, which drives a steady expansion and cooling of the outer envelope of the star. As the star gets larger in radius and its surface temperature cools, it becomes a red giant.

red giant region The upper-right-hand corner of the Hertzsprung–Russell diagram, where red-giant stars are found.

red shift Motion-induced change in the wavelength of light emitted from a source moving away from us. The relative recessional motion causes the wave to have an observed wavelength longer (and hence redder) than it would if it were not moving.

red supergiant An extremely luminous red star. Often found on the asymptotic giant branch of the H-R diagram.

reddening Dimming of starlight by interstellar matter, which tends to scatter higher-frequency (blue) components of the radiation more efficiently than the lower-frequency (red) components.

reflecting telescope A telescope which uses a mirror to gather and focus light from a distant object.

refracting telescope A telescope which uses a lens to gather and focus light from a distant object.

refraction The tendency of a wave to bend as it passes from one transparent medium to another.

residual cap Portion of Martian polar ice caps that remains permanently frozen, undergoing no seasonal variations.

retrograde motion Backward, westward loop traced out by a planet with respect to the fixed stars.

revolution Orbital motion of one body about another, such as the Earth about the Sun.

right ascension Celestial coordinate used to measure longitude on the celestial sphere. The zero point is the position of the Sun on the vernal equinox.

rille A ditch on the surface of the Moon where molten lava flowed in the past.

ringlet Narrow region in Saturn's planetary ring system where the density of ring particles is high. *Voyager* discovered that the rings visible from Earth are actually composed of tens of thousands of ringlets.

Roche limit Often called the tidal stability limit, the Roche limit gives the distance from a planet at which the tidal force, due to the planet, between adjacent objects exceeds their mutual attraction. Objects within this limit are unlikely to accumulate into larger objects. The rings of Saturn occupy the region within Saturn's Roche limit.

Roche lobes An imaginary surface around a star. Each star in a binary system can be pictured as being surrounded by a tear-shaped zone of gravitational influence, the Roche lobe. Any material within the Roche lobe of a star can be considered to be part of that star. During evolution, one member of the binary star can expand so that it overflows its own Roche lobe, and begins to transfer matter onto the other star.

rotation Spinning motion of a body about an axis.

rotation curve Plot of the orbital speed of disk material in a galaxy against its distance from the galactic center. Analysis of rotation curves of spiral galaxies indicates the existence of dark matter.

RR Lyrae star Variable star whose luminosity changes in a characteristic way. All RR Lyrae stars have more or less the same period.

runaway greenhouse effect A process in which the heating of a planet leads to an increase in its atmosphere's ability to retain heat and thus to further heating, quickly causing extreme changes in the temperature of the surface and the composition of the atmosphere.

runoff channel River-like surface feature on Mars, evidence that liquid water once existed there in great quantities. Runoff channels are found in the southern highlands, and are thought to have been formed by water that flowed nearly 4 billion years ago.

G

galactic bulge Thick distribution of warm gas and stars around the galactic center.

galactic cannibalism A galaxy merger in which a larger galaxy consumes a smaller one.

galactic center The center of the Milky Way, or any other, galaxy. The point about which the disk of a spiral galaxy rotates.

galactic disk Flattened region of gas and dust that bisects the galactic halo in a spiral galaxy. This is the region of active star formation.

galactic halo Region of a galaxy extending far above and below the galactic disk, where globular clusters and other old stars reside.

galactic nucleus Small central high-density region of a galaxy. Nearly all of the radiation from an active galaxy is emitted from the nucleus.

galaxy Gravitationally bound collection of a large number of stars. The Sun is a star in the Milky Way Galaxy.

galaxy cluster A collection of galaxies held together by their mutual gravitational attraction.

Galilean satellites The four brightest and largest moons of Jupiter (Io, Europa, Ganymede, Callisto), named after Galileo Galilei, the 17th century astronomer who first observed them.

gamma ray Region of the electromagnetic spectrum, far beyond the visible spectrum, corresponding to radiation of very high frequency and very short wavelength.

gamma-ray burst Object that radiates tremendous amounts of energy in the form of gamma rays, possibly due to the collision and merger of two neutron stars initially in orbit around one another.

general theory of relativity Einstein's theory of gravity, in which the force of gravity is reinterpreted as a curvature of spacetime in the vicinity of a massive object.

geocentric model A model of the solar system which holds that the Earth is at the center of the universe and all other bodies are in orbit around it. The earliest theories of the solar system were geocentric.

giant A star with a radius between 10 and 100 times that of the Sun.

globular cluster Tightly bound, roughly spherical collection of hundreds of thousands, and sometimes millions, of stars, spanning about 50 parsecs. Globular clusters are distributed in the halos around the Milky Way and other galaxies.

Grand Unified Theories Class of theories describing the behavior of the single force that results from unification of the strong, weak, and electromagnetic forces in the early universe.

granulation Mottled appearance of the solar surface, caused by rising (hot) and falling (cool) material in convective cells just below the photosphere.

gravitational field Field created by any object with mass, extending outward in all directions, which determines the influence of that object on all others. The strength of the gravitational field decreases as the square of the distance.

gravitational lensing The effect induced on the image of a distant object by a massive foreground object. Light from the distant object is bent into two or more separate images.

gravitational red shift A prediction of Einstein's general theory of relativity. Photons lose energy as they escape the gravitational field of a massive object. Because a photon's energy is proportional to its frequency, a photon that loses energy suffers a decrease in frequency, which corresponds to an increase, or redshift, in wavelength.

gravity The attractive effect that any massive object has on all other massive objects. The greater the mass of the object, the stronger its gravitational pull.

Great Dark Spot Prominent storm system in the atmosphere of Neptune, located near the equator of the planet. The system is comparable in size to the Earth.

Great Red Spot A large, high-pressure, long-lived storm system visible in the atmosphere of Jupiter. The Red Spot is roughly twice the size of the Earth.

greenhouse effect The partial trapping of solar radiation by a planetary atmosphere, similar to the trapping of heat in a greenhouse.

ground state The lowest energy state that an electron can have within an atom.

E

E ring A faint ring, well outside the main ring system of Saturn, which was discovered by *Voyager* and is believed to be associated with volcanism on the moon Enceladus.

Earth-crossing asteroid An asteroid whose orbit crosses that of the Earth. Earth-crossing asteroids are also called Apollo asteroids, after the first of the type discovered.

earthquake A sudden dislocation of rocky material near the Earth's surface.

eccentricity A measure of the flatness of an ellipse, equal to the distance between the two foci divided by the length of the major axis.

eclipse Event during which one body passes in front of another, so that the light from the occulted body is blocked.

eclipse season Times of the year when the Moon lies in the same plane as the Earth and Sun, so that eclipses are possible.

eclipsing binary Rare binary-star system that is aligned in such a way that from Earth we periodically observe one star pass in front of the other, eclipsing the other star.

ecliptic The apparent path of the Sun, relative to the stars on the celestial sphere, over the course of a year.

electric field A field extending outward in all directions from a charged particle, such as a proton or an electron. The electric field determines the electric force exerted by the particle on all other charged particles in the universe; the strength of the electric field decreases with increasing distance from the charge according to an inverse-square law.

electromagnetic radiation Another term for light, electromagnetic radiation transfers energy and information from one place to another, even through the vacuum of empty space.

electromagnetic spectrum The complete range of electromagnetic radiation, from radio waves to gamma rays, including the visible spectrum. All types of electromagnetic radiation are basically the same phenomenon, differing only by wavelength, and all move at the speed of light.

electromagnetism The union of electricity and magnetism, which do not exist as independent quantities, but are in reality two aspects of a single physical phenomenon.

electron An elementary particle with a negative electric charge, one of the components of the atom.

electron degeneracy pressure The pressure produced by the resistance of electrons to compression once they are squeezed to the point of contact.

element Matter made up of one particular atom. The number of protons in the nucleus of the atom determines which element it represents.

ellipse Geometric figure resembling an elongated circle. An ellipse is characterized by its degree of flatness, or eccentricity, and the length of its long axis. In general, bound orbits of objects moving under gravity are elliptical.

elliptical galaxy Category of galaxy in which the stars are distributed in an elliptical shape on the sky, ranging from highly elongated to nearly circular in appearance.

emission line Bright line in a specific location of the spectrum of radiating material, corresponding to emission of light at a certain frequency. A heated gas in a glass container produces emission lines in its spectrum.

emission nebula A glowing cloud of hot interstellar gas. The gas glows as a result of a nearby young star which is ionizing the gas. Since this gas is mostly hydrogen, the emitted radiation falls predominantly in the red region of the spectrum, because of a dominant hydrogen emission line.

emission spectrum The pattern of spectral emission lines produced by an element. Each element has its own unique emission spectrum.

Encke Gap A small gap in Saturn's A ring.

epicycle A construct of the geocentric model of the solar system which was necessary to explain observed planetary motions. Each planet rides on a small epicycle whose center in turn rides on a larger circle (the deferent).

equinox See autumnal equinox and vernal equinox.

escape speed The speed necessary for an object to escape the gravitational pull of an object. Anything that moves away from the object with more than the escape speed will never return.

event horizon Imaginary spherical surface surrounding a collapsing star, with radius equal to the Schwarzschild radius, within which no event can be seen, heard, or known about by an outside observer.

evolutionary theory A theory which explains observations in a series of gradual steps, explainable in terms of well-established physical principles.

evolutionary track A graphical representation of a star's life as a path on the Hertzsprung&151;Russell diagram.

excited state State of an atom when one of its electrons is in a higher energy orbital than the ground state. Atoms can become excited by absorbing a photon of a specific energy, or by colliding with a nearby atom.

extinction The dimming of starlight as it passes through the interstellar medium.

D

D ring Collection of very faint, thin rings, extending from the inner edge of the C ring down nearly to the cloud tops of Saturn. This region contains so few particles that it is completely invisible from Earth.

dark dust cloud A large cloud, often many parsecs across, which contains gas and dust in a ratio of about 10^{12} gas atoms for every dust particle. Typical densities are a few tens or hundreds of millions of particles per cubic meter.

dark halo Region of a galaxy beyond the visible halo where dark matter is believed to reside.

dark matter Term used to describe the mass in galaxies and clusters whose existence we infer from rotation curves and other techniques, but which has not been confirmed by observations at any electromagnetic wavelength.

declination Celestial coordinate used to measure latitude above or below the celestial equator on the celestial sphere.

decoupling Event in the early universe when atoms first formed, and after which photons could propagate freely through space.

deferent A construct of the geocentric model of the solar system which was needed to explain observed planetary motions. A deferent is a large circle encircling the Earth, on which an epicycle moves.

degree See arc degree.

density A measure of the compactness of the matter within an object, computed by dividing the mass by the volume of the object. Units are kilograms per cubic meter (kg/m^3), or grams per cubic centimeter (g/cm^3).

deuteron An isotope of hydrogen in which there is a neutron bound to the proton in the nucleus. Often called “heavy hydrogen” because of the extra mass of the neutron.

differential rotation The tendency for a gaseous sphere, such as a jovian planet or the Sun, to rotate at a different rate at the equator than at the poles or for the rotation rate to vary with depth. For a galaxy or other object, a condition where the angular speed varies with location within the object.

differentiation Variation with depth in the density and composition of a body, such as Earth, with low-density material on the surface and higher density material in the core.

diffraction The tendency of waves to bend around corners. The diffraction of light establishes its nature as a wave.

Doppler effect Any motion-induced change in the observed wavelength (or frequency) of a wave.

Drake Equation Expression that gives an estimate of the probability that intelligence exists elsewhere in the galaxy, based on a number of supposedly necessary conditions for intelligent life to develop.

dust grain An interstellar dust particle, roughly 10&150;8 m in size, comparable to the wavelength of visible light.

dust lane A lane of dark, obscuring interstellar dust in an emission nebula or galaxy.

dust tail The component of a comet's tail that is composed of dust particles.

dwarf Any star with radius comparable to, or smaller than, that of the Sun (including the Sun itself).

dynamo theory Theory that explains planetary and stellar magnetic fields in terms of rotating, conducting material flowing in an object's interior.

P

parallax The apparent motion of a relatively close object with respect to a more distant background as the location of the observer changes.

parsec The distance at which a star must lie in order that its measured parallax is exactly 1 arc second, equal to 206,000 A.U.

pair production The process in which two photons of electromagnetic radiation give rise to a particle—anti-particle pair.

partial eclipse Celestial event during which only a part of the occulted body is blocked from view.

penumbra Portion of the shadow cast by an eclipsing object in which the eclipse is seen as partial.

perihelion The closest approach to the Sun of any object in orbit about it.

period The time needed for an orbiting body to complete one revolution about another body.

period-luminosity relation A relation between the pulsation period of a Cepheid variable and its absolute brightness. Measurement of the pulsation period allows the distance of the star to be determined.

permafrost Layer of permanently frozen water ice believed to lie just under the surface of Mars.

photoelectric effect Experiment concerning the detection of electrons from a metal surface, whose speed off the surface was dependent on the frequency of light striking the surface. The theoretical explanation rests on viewing light as made up of photons, or individual bullets of energy.

photometer A device that measures the total amount of light received in all or part of the image.

photometry Branch of observational astronomy in which intensity measurements are made through each of a set of standard filters.

photon Individual packet of electromagnetic energy that makes up electromagnetic radiation.

photosphere The visible surface of the Sun, lying just above the uppermost layer of the Sun's interior, and just below the chromosphere.

pixel One of many tiny picture elements, organized into an array, making up a digital image.

Planck curve see blackbody curve

planet One of nine major bodies that orbit the Sun, visible to us by reflected sunlight.

planetary nebula The ejected envelope of a red giant star, spread over a volume roughly the size of our solar system.

planetary ring system Material organized into thin, flat rings encircling a giant planet, such as Saturn.

planetesimal Term given to objects in the early solar system that had reached the size of small moons, at which point their gravitational fields were strong enough to begin to influence their neighbors.

plate tectonics The motions of regions of Earth's crust, which drift with respect to one another. Also known as continental drift.

polarization The alignment of the electric fields of emitted photons, which are generally emitted with random orientations.

positron Atomic particle with properties identical to those of a negatively charged electron, except for its positive charge. The positron is the antiparticle of the electron. Positrons and electrons annihilate one another when they meet, producing pure energy in the form of gamma rays.

precession The slow change in the direction of the axis of a spinning object, caused by some external influence.

primary atmosphere The chemical components that would have surrounded Earth just after it formed.

prime focus The point in a reflecting telescope where the mirror focuses incoming light to a point.

primordial nucleosynthesis The production of elements heavier than hydrogen by nuclear fusion in the high temperatures and densities which existed in the early universe.

Principle of Cosmic Censorship A proposition to separate the unexplained physics near a singularity from the rest of the well-behaved universe. The principle states that nature always hides any singularity, such as a black hole, inside an event horizon, which insulates the rest of the universe from seeing it.

prominence Loop or sheet of glowing gas ejected from an active region on the solar surface, which then moves through the inner parts of the corona under the influence of the Sun's magnetic field.

proper motion The angular movement of a star across the sky, as seen from Earth, measured in seconds of arc per year. This movement is a result of the star's actual motion through space.

proton An elementary particle carrying a positive electric charge, a component of all atomic nuclei. The number of protons in the nucleus of an atom dictates what type of atom it is.

proton-proton chain The chain of fusion reactions, leading from hydrogen to helium, that powers most main-sequence stars.

protoplanet Clump of material, formed in the early stages of solar system formation, that was the forerunner of the planets we see today.

protostar Stage in star formation when the interior of a collapsing fragment of gas is sufficiently hot and dense that it becomes opaque to its own radiation. The protostar is the dense region at the center of the fragment.

protosun The central accumulation of material in the early stages of solar system formations, the forerunner of the present-day Sun.

Ptolemaic model Geocentric solar system model, developed by the second century astronomer Claudius Ptolemy. It predicted with great accuracy the positions of the then known planets.

pulsar Object that emits radiation in the form of rapid pulses with a characteristic pulse period and duration. Charged particles, accelerated by the magnetic field of a rapidly rotating neutron star, flow along the magnetic field lines, producing radiation that beams outward as the star spins on its axis.

pulsating variable star A star whose luminosity varies in a predictable, periodic way.

H

heliocentric model A mode of the solar system which is centered on the Sun, with the Earth in motion about the Sun.

helioseismology The study of conditions far below the Sun's surface through the analysis of internal "sound" waves that repeatedly cross the solar interior.

helium capture The formation of heavy elements by the capture of a helium nucleus. For example, carbon can form heavier elements by fusion with other carbon nuclei, but it is much more likely to occur by helium capture, which requires less energy.

helium flash An explosive event in the post-main-sequence evolution of a low-mass star. When helium fusion begins in a dense stellar core, the burning is explosive in nature. It continues until the energy released is enough to expand the core, at which point the star achieves stable equilibrium again.

helium precipitation Mechanism responsible for the low abundance of helium of Saturn's atmosphere. Helium condenses in the upper layers to form a mist, which rains down toward Saturn's interior, just as water vapor forms into rain in the atmosphere of Earth.

Hertzsprung–Russell (H—R) diagram A plot of luminosity against temperature (or spectral class) for a group of stars.

high-energy telescope Telescope designed to detect radiation in X-rays and gamma rays.

highlands Relatively light-colored regions on the surface of the Moon which are elevated several kilometers above the maria. Also called terrae.

homogeneity Assumed property of the universe such that the number of galaxies in an imaginary large cube of the universe is the same no matter where in the universe the cube is placed.

horizon problem One of two conceptual problems with the standard Big Bang model, which is that some regions of the universe which have very similar properties are too far apart to have exchanged information in the age of the universe.

horizontal branch Region of the Hertzsprung–Russell diagram where post–main sequence stars again reach hydrostatic equilibrium. At this point, the star is burning helium in its core, and hydrogen in a shell surrounding the core.

hot dark matter A class of candidates for the dark matter in the universe, composed of lightweight particles, such as neutrinos, much less massive than the electron.

Hubble classification scheme Method of classifying galaxies according to their appearance, developed by Edwin Hubble.

Hubble's constant The constant of proportionality which gives the relation between recessional velocity and distance in Hubble's law.

Hubble's law Law that relates the observed velocity of recession of a galaxy to its distance from us. The velocity of recession of a galaxy is directly proportional to its distance away.

hydrogen envelope An invisible region engulfing the coma of a comet, usually distorted by the solar wind, and extending across millions of kilometers of space.

hydrogen shell burning Fusion of hydrogen in a shell that is driven by contraction and heating of the helium core. Once hydrogen is depleted in the core of a star, hydrogen burning stops and the core contracts due to gravity, causing the temperature to rise, heating the surrounding layers of hydrogen in the star, and increasing the burning rate there.

hydrosphere Layer of the Earth which contains the liquid oceans and accounts for roughly 70 percent of Earth's total surface area.

1.5 The Measurement of Distance

5 We have seen a little of how ancient astronomers tracked and recorded the positions of the stars on the sky and how modern astronomers make similar observations. But knowing the directions in which objects lie is only part of the information needed to locate them in space. Before we can make a systematic study of the heavens, we must find a way of measuring *distances*, too. One distance-measurement method, called **triangulation**, is based on the principles of Euclidean geometry and finds widespread application today in both terrestrial and astronomical settings. Today's engineers, especially surveyors, use these age-old geometric ideas to measure indirectly the distance to faraway objects. Triangulation forms the foundation of the family of distance-measurement techniques that together make up the **cosmic distance scale**.

Imagine trying to measure the distance to a tree on the other side of a river. The most direct method is to lay a tape across the river, but that's not the simplest way. A smart surveyor would make the measurement by visualizing an *imaginary* triangle (hence *triangulation*), sighting the tree on the far side of the river from two positions on the near side, as illustrated in Figure 1.22. The simplest possible triangle is a right triangle, in which one of the angles is exactly 90°, so it is usually convenient to set up one observation position directly opposite the object, as at point A. The surveyor then moves to another observation position at point B, noting the distance covered between points A and B. This distance is called the **baseline** of the imaginary triangle. Finally, the surveyor, standing at point B, sights toward the tree and notes the angle at point B between this sightline and the baseline. No further observations are required. Knowing the value of one side (AB) and two angles (the right angle itself, at point A, and the angle at point B) of the right triangle, the surveyor can geometrically construct the remaining sides and angles and so establish the distance from A to the tree.

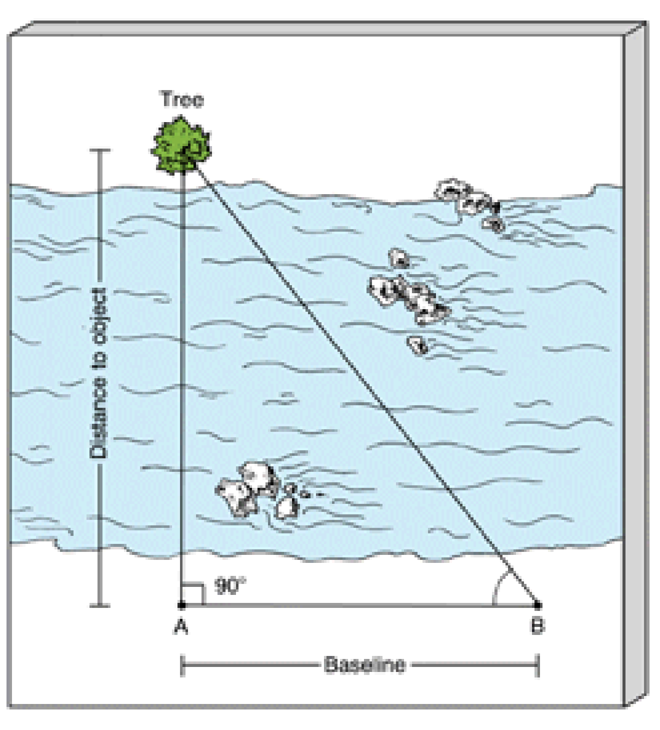


Figure 1.22 Surveyors often use simple geometry and trigonometry to estimate the distance to a faraway object.

To use triangulation to measure distances, a surveyor must be familiar with *trigonometry*, the mathematics of geometrical angles. However, even if we know no trigonometry at all, we can still solve the problem by graphical means, as shown in Figure 1.23. Suppose that we pace off the baseline AB, measuring it to be 450 meters, and measure the angle between the baseline and the line from B to the tree to be 52°, as illustrated in the figure. We can transfer the problem to paper by letting one box on our graph represent 25 meters on the ground. Drawing the line AB on paper, completing the other two sides of the triangle, at angles of 90° (at A) and 52° (at B), we measure the distance on paper from A to the tree to be 23 boxes—that is, 575 meters. We have solved the real problem by *modeling* it on paper. The point to remember here is this: nothing more complex than basic geometry is needed to infer the distance, the size, and even the shape of an object too far away or too inaccessible for direct measurement.

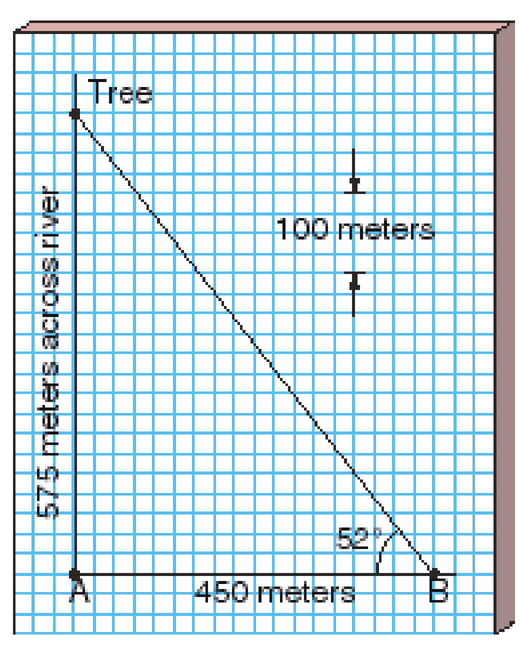


Figure 1.23 We don't even need trigonometry to estimate distances indirectly. Scaled estimates, like this one on a piece of paper, often suffice.

Triangles with larger baselines are needed if we are to measure greater distances. Figure 1.24 shows a triangle having a fixed baseline between two observation positions at points A and B. Note how the triangle becomes narrower as an object's distance becomes progressively greater. Narrow triangles cause problems because the angles at points A and B are hard to measure accurately. The measurements can be made easier by "fattening" the triangle—in other words, by lengthening the baseline.

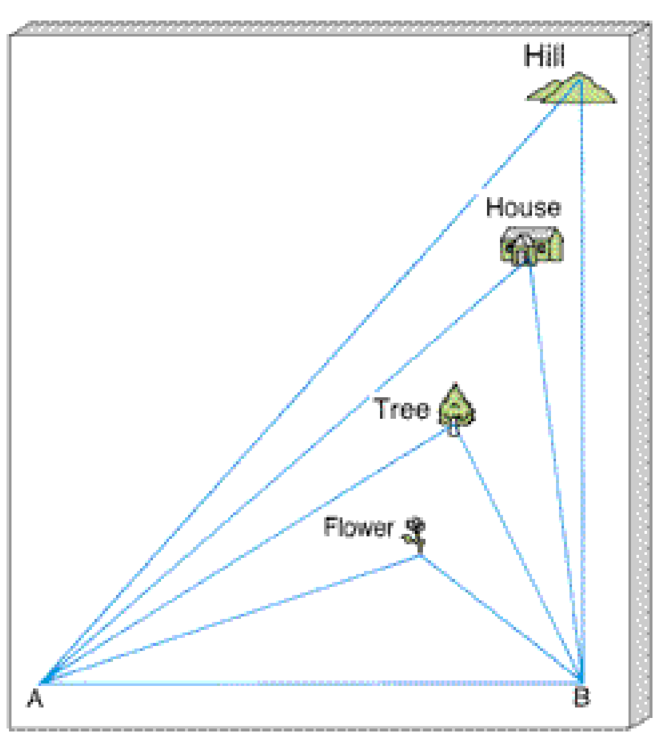


Figure 1.24 A triangle of fixed baseline (distance between points A and B) is narrower the farther away the object. As shown here, the imaginary triangle is much thinner when estimating the distance to a remote hill than it is when estimating the distance to a nearby flower.

Now consider an imaginary triangle extending from Earth to a nearby object in space, perhaps a neighboring planet. The imaginary triangle is extremely long and narrow, even for the nearest cosmic objects. Figure 1.25(a) illustrates the case in which the longest baseline on Earth—Earth's diameter, measured from point A to point B—is used. In principle, two observers could sight the planet from opposite sides of Earth, measuring the triangle's angles at points A and B. In practice, though, these angles cannot be measured with sufficient precision. It is actually easier to measure the third angle of the imaginary triangle, namely, the very small one near the planet. Here's how.

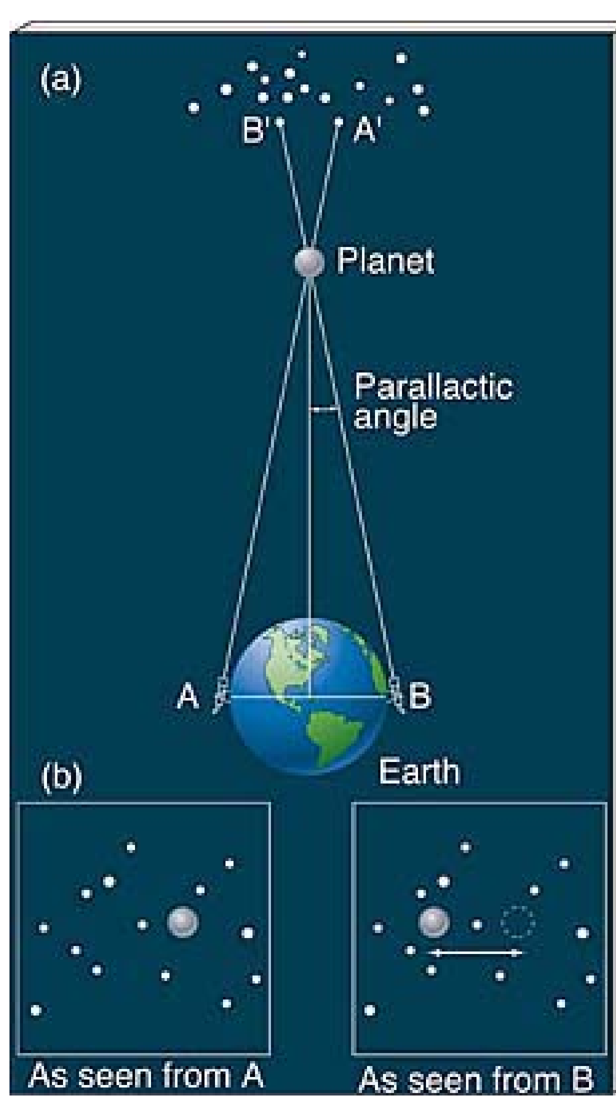


Figure 1.25 (a) This imaginary triangle extends from Earth to a nearby object in space (such as a planet). The group of stars at the top represents a background field of very distant stars. (b) Hypothetical photographs of the same star field showing the nearby object's apparent displacement, or shift, relative to the distant, undisplaced stars.

The observers on either side of Earth sight toward the planet, taking note of its position *relative to some distant stars* seen on the plane of the sky. The observer at point A sees the planet at apparent location A' relative to those stars, as indicated in Figure 1.25(a). The observer at B sees the planet at point B'. If each observer takes a photograph of the appropriate region of the sky, the planet will appear at slightly different places in the two images. In other words, the planet's photographic image is slightly displaced, or shifted, relative to the field of distant background stars, as shown in Figure 1.25(b). The background stars themselves appear undisplaced because of their much greater distance from the observer. This apparent displacement of a foreground object relative to the background as the observer's location changes is known as **parallax**. The size of the shift in Figure 1.25(b), measured as an angle on the celestial sphere, is equal to the third, small angle shown in Figure 1.25(a).

The closer an object is to the observer, the larger the parallax. To see this for yourself, hold a pencil vertically in front of your nose, as sketched in Figure 1.26. Concentrate on some far-off object—a distant wall, say. Close one eye, then open it while closing the other. By blinking in this way, you should be able to see a large shift of the apparent position of the pencil projected onto the distant wall—a large parallax. In this example, one eye corresponds to point A, the other eye to point B, the distance between your eyeballs to the baseline, the pencil to the planet, and the distant wall to a remote field of stars. Now hold the pencil at arm's length, corresponding to a more distant object (but still not as far away as the distant stars). The apparent shift of the pencil will be less. By moving the pencil farther away, we are narrowing the triangle and decreasing the parallax (and, in the process, making its accurate measurement more difficult). If you were to paste the pencil to the wall, corresponding to the case where the object of interest is as far away as the background star field, blinking would produce no apparent shift of the pencil at all.

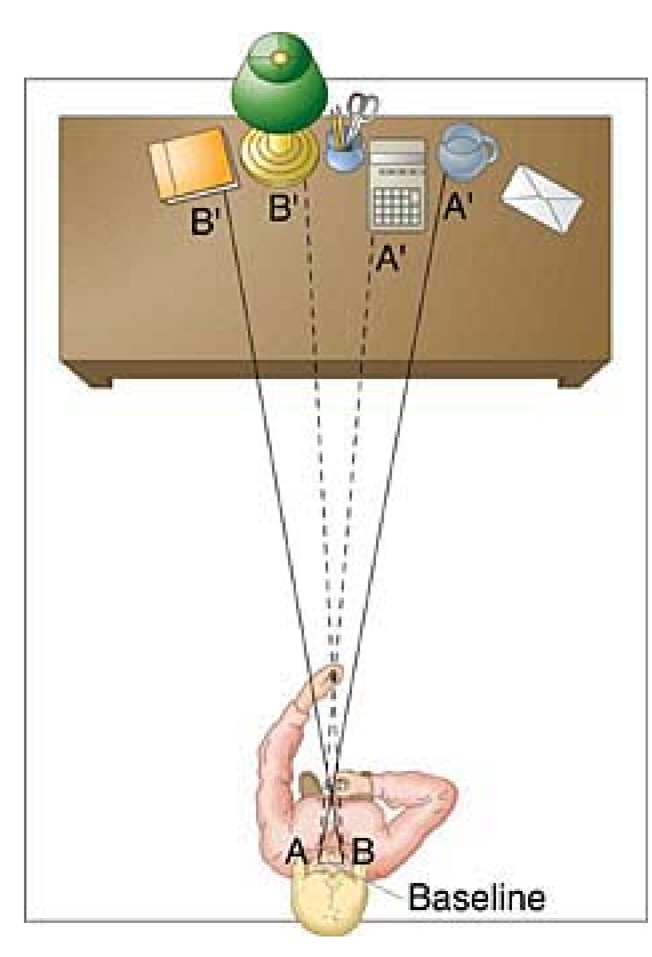


Figure 1.26 Parallax is inversely proportional to an object's distance. An object near your nose has a much larger parallax than an object held at arm's length.

The amount of parallax is thus inversely proportional to an object's distance. Small parallax implies large distance, and large parallax implies small distance. Knowing the amount of parallax (as an angle) and the length of the baseline, we can easily derive the distance through triangulation.

Once we know the distance to an object, we can determine many other properties. In particular, by measuring the object's *angular diameter* we can calculate its size. Figure 1.27 illustrates the geometry involved. Notice that this is basically the same picture as Figure 1.25(a), except that the angle (the angular diameter) and the distance are known, instead of the angle (the parallax) and the baseline. We compute the object's diameter by noting that the ratio of the diameter to the circumference of the circle centered on the observer and passing through the object (2π times the distance) must be equal to the ratio of its angular diameter to one full revolution, 360° :

$$\frac{\text{diameter}}{2\pi \times \text{distance}} = \frac{\text{angular diameter}}{360°}.$$

Surveyors of the land routinely use such simple geometric techniques to map out planet Earth (see *More Precisely 1-3* for an early example). As surveyors of the sky, astronomers use the same basic principles to chart the universe.

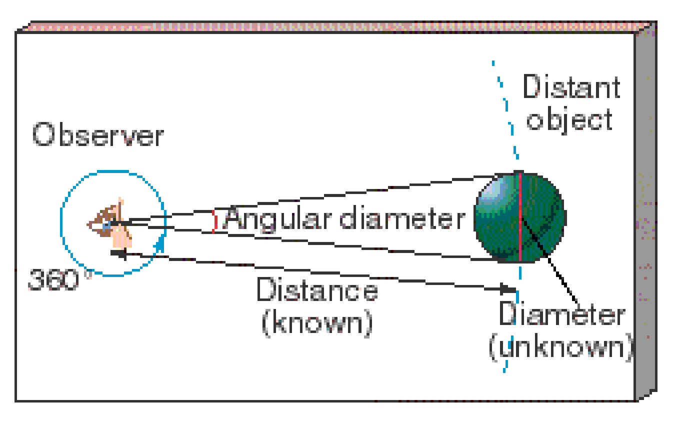


Figure 1.27 If the angular diameter of a distant object can be measured and its distance is known, its true diameter may be calculated by simple geometry.

PREVIOUS NEXT CHAPTER REVIEW

T

T Tauri star Protostar in the late stages of formation, often exhibiting violent surface activity. T Tauri stars have been observed to brighten noticeably in a short period of time, consistent with the idea of rapid evolution during this final phase of stellar formation.

tail Component of a comet that consists of material streaming away from the main body, sometimes spanning hundreds of millions of kilometers. May be composed of dust or ionized gases.

telescope Instrument used to capture as many photons as possible from a given region of the sky and concentrate them into a focused beam for analysis.

temperature A measure of the amount of heat in an object, and an indication of the speed of the particles that comprise it.

terrae See highlands.

terrestrial planet The four innermost planets of the solar system, resembling the Earth in general physical and chemical properties.

theories of relativity Einstein's theories, on which much of modern physics rests. Two essential facts of the theory are that nothing can travel faster than the speed of light, and that everything, including light, is affected by gravity.

thick disk Region of a spiral galaxy where an intermediate population of stars resides, younger than the halo stars, but older than stars in the disk.

tidal bulge Elongation of the Earth caused by the difference between the gravitational force on the side nearest the Moon and the force on the side farthest from the Moon. The long axis of the tidal bulge points toward the Moon. More generally, the deformation of any body produced by the tidal effect of a nearby gravitating object.

tidal force The variation in one body's gravitational force from place to place across another body–for example, the variation of the Moon's gravity across the Earth.

tides Rising and falling motion that bodies of water follow, exhibiting daily, monthly, and yearly cycles. Ocean tides on Earth are caused by the competing gravitational pull of the Moon and Sun on different regions of the Earth.

time dilation A prediction of the theory of relativity, closely related to the gravitational reshift. To an outside observer, a clock lowered into a strong gravitational field will appear to run slow.

total eclipse Celestial event during which one body is completely blocked from view by another.

total solar eclipse Celestial event during which one body is completely blocked from view by another.

transition zone The region of rapid temperature increase that separates the Sun's chromosphere from the corona.

transverse motion Motion perpendicular to a particular line of sight, which does not result in Doppler shift in radiation received.

triangulation Method of determining distance based on the principles of geometry. A distant object is sighted from two well-separated locations. The distance between the two locations and the angle between the line joining them and the line to the distant object are all that are necessary to ascertain the object's distance.

triple-alpha process The generation of Carbon-12 from the fusion of three helium-4 nuclei (alpha particles). Helium-burning stars occupy a region of the H-R diagram known as the horizontal branch.

Trojan asteroids One of two groups of asteroids which orbit at the same distance from the Sun as Jupiter, 60 degrees ahead and behind the planet.

tropical year The time interval between one vernal equinox and the next.

troposphere The portion of Earth's atmosphere from the surface to about 15 km.

Tully-Fisher relation A relation used to determine the absolute luminosity of a spiral galaxy. The rotational velocity, measured from the broadening of spectral lines, is related to the total mass, and hence the total luminosity.

21-centimeter radiation Radio radiation emitted when an electron in the ground state of a hydrogen atom flips its spin to become parallel to the spin of the proton in the nucleus.

Type I supernova One possible explosive death of a star. A white dwarf in a binary system can accrete enough mass that it cannot support its own weight. The star collapses and temperatures become high enough for carbon fusion to occur. Fusion begins throughout the white dwarf almost simultaneously and an explosion results.

Type II supernova One possible explosive death of a star, in which the highly evolved stellar core rapidly implodes and then explodes, destroying the surrounding star.

B

B ring One of three Saturnian rings visible from Earth. The B ring is the brightest of the three, and lies just within the Cassini division, closer to the planet than the A ring.

barred-spiral galaxy Spiral galaxy in which a bar of material passes through the center of the galaxy, with the spiral arms beginning near the ends of the bar.

baseline The distance between two observing locations used for the purposes of triangulation measurements. The larger the baseline, the better the resolution attainable.

belt Dark, low-pressure region in the atmosphere of a jovian planet where gas flows downward.

Big Bang Event that cosmologists consider the beginning of the universe, in which all matter and radiation in the entire universe came into being.

binary-star system A system which consists of two stars in orbit about their common center of mass, held together by their mutual gravitational attraction. Most stars are found in binary-star systems.

blackbody curve The characteristic way in which the intensity of radiation emitted by a hot object depends on frequency. The frequency at which the emitted intensity is highest is an indication of the temperature of the radiating object. Also referred to as the Planck curve.

black dwarf The end-point of the evolution of an isolated, low-mass star. After the white dwarf stage, the star cools to the point where it is a dark clinker in interstellar space.

black hole A region of space where the pull of gravity is so great that nothing-not even light-can escape. A possible outcome of the evolution of a very massive star.

blue giant Large, hot, bright star at the upper left end of the main sequence on the Hertzsprung–Russell diagram. Its name comes from its color and size.

blue shift Motion-induced changed in the observed wavelength from a source that is moving toward us. Relative approaching motion between the object and the observer causes the wavelength to appear shorter (and hence bluer) than if there were no motion at all.

blue supergiant The very largest of the large, hot, bright stars at the uppermost left end of the main sequence on the Hertzsprung–Russell diagram.

Bohr model First theory of the hydrogen atom to explain the observed spectral lines. This model rests on three ideas: that there is a state of lowest energy for the electron, that there is a maximum energy, beyond which the electron is no longer bound to the nucleus, and that within these two energies the electron can only exist in certain energy levels.

brown dwarf Remnant of a fragment of collapsing gas and dust that did not contain enough mass to initiate core nuclear fusion. Such objects are frozen somewhere along their pre-main-sequence contraction phase, continually cooling into compact dark objects. Because of their small sizes and low temperatures they are extremely difficult to detect observationally.

brown oval Feature of Jupiter's atmosphere that appears only at latitudes near 20 degrees N, this structure is a long-lived hole in the clouds that allows us to look down into Jupiter's lower atmosphere.

MORE PRECISELY 1-3 Earth Dimensions

In about 200 b.c. a Greek philosopher named Eratosthenes (276—194 b.c.) used simple geometric reasoning to calculate the size of Earth. The logic he employed still provides the basis for all measurements of distance outside of our own solar system. Eratosthenes knew that at noon on the first day of summer, observers in the city of Syene (now called Aswan), in Egypt, saw the Sun pass directly overhead. This was evident from the fact that vertical objects cast no shadows and sunlight reached to the very bottoms of deep wells, as shown in the insets in the accompanying figure. However, at noon of the same day in Alexandria, a city 5000 *stadia* to the north, the Sun was seen to be displaced slightly from the vertical. (The *stadium* was a Greek unit of length, believed to have been about 0.16 km, although the exact value is uncertain—not all Greek stadia were the same size!) Using the simple technique of measuring the length of the shadow of a vertical stick and applying elementary trigonometry, Eratosthenes determined the angular displacement of the Sun from the vertical at Alexandria to be 7.2 °.

What could have caused this discrepancy between the two measurements? It was not the result of measurement error—the same results were obtained every time the observations were repeated. Instead, as illustrated in the figure, the explanation is simply that Earth's surface is not flat but is actually *curved*. Our planet is a sphere. Eratosthenes was not the first person to realize that Earth is spherical—the philosopher Aristotle had done that over 100 years earlier (see Interlude 2-2)—but he was apparently the first to build on this knowledge, combining geometry with direct measurement to infer the size of our planet. Here's how he did it.

Rays of light reaching Earth from a very distant object, such as the Sun, travel almost parallel to one another. Consequently, as shown in the figure, the angle measured at Alexandria between the Sun's rays and the vertical (that is, the line joining Alexandria to the center of Earth) is equal to the angle between Syene and Alexandria, as seen from Earth's center. (For the sake of clarity, this angle has been exaggerated in the drawing.)

The size of this angle in turn is proportional to the fraction of Earth's circumference that lies between Syene and Alexandria. Since 7.2 ° is 1/50 of a full circle (360 °), so Earth's entire circumference can be estimated by multiplying the distance between the two cities by a factor of 50. We can express this reasoning as follows:

$$\frac{7.2^\circ}{360^\circ} = \frac{5000 \text{ stadia}}{\text{Earth's circumference}}.$$

(Notice that this is precisely the same geometric reasoning as that presented in Section 1.5.) Earth's circumference is therefore 50×5000, or 250,000 stadia. If we take the stadium unit to be 0.16 km, we find that Eratosthenes estimated Earth's circumference to be about 40,000 km. Since the circumference C of a circle is related to its radius r by the relation $C = 2\pi r$, it follows that Earth's radius is $250{,}000/2\pi$ stadia, or 6366 km. The correct values for Earth's circumference and radius, now measured accurately by orbiting spacecraft, are 40,070 km and 6378 km, respectively.

Eratosthenes' reasoning was a remarkable accomplishment. More than 20 centuries ago, he estimated the circumference of Earth to within 1 percent accuracy, using only simple geometry. Even if our modern value for the size of one stadium turns out to be incorrect, the real achievement—that a person making measurements on only a small portion of Earth's surface was able to compute the size of the entire planet on the basis of observation and logic—is undiminished.

L

Lagrange point One of five special points in the plane of two massive bodies orbiting one another, where a third body of negligible mass can remain in equilibrium.

law of conservation of mass and energy A fundamental law of modern physics which states that the sum of mass and energy must always remain constant in any physical process. In fusion reactions, the lost mass is converted into energy, primarily in the form of electromagnetic radiation.

laws of planetary motion Three laws, based on precise observations of the motions of the planets by Tycho Brahe, which summarize the motions of the planets about the Sun.

lava dome Volcanic formations formed when lava oozes out of fissures in a planet's surface, creating the dome, and then withdraws, causing the crust to crack and subside.

light See electromagnetic radiation.

light curve A plot of the variation in brightness of a star with time.

lighthouse model The leading explanation for pulsars. A small region of the neutron star, near one of the magnetic poles, emits a steady stream of radiation which sweeps past Earth each time the star rotates. The period of the pulses is the star's rotation period.

light year The distance that light, moving at a constant speed of 300,000 km/s, travels in one year. One light year is about 10 trillion kilometers.

line of nodes The line of intersection of the Moon's orbit with the ecliptic plane.

lithosphere Earth's crust and a small portion of the upper mantle that make up Earth's plates. This layer of the Earth undergoes tectonic activity.

Local Group The small galaxy cluster that includes the Milky Way Galaxy.

luminosity One of the basic properties used to characterize stars, luminosity is defined as the total energy radiated by a star each second, at all wavelengths.

luminosity class A classification scheme which groups stars according to the width of their spectral lines. For a group of stars with the same temperature, luminosity class differentiates between supergiants, giants, main-sequence stars, and subdwarfs.

lunar eclipse Celestial event during which the Moon passes through the shadow of the Earth, temporarily darkening its surface.

lunar phases The appearance of the moon at different points along its orbit.

F

F ring Faint narrow outer ring of Saturn, discovered by *Pioneer* in 1979. The F ring lies just inside the Roche limit of Saturn, and was shown by *Voyager* to be made up of several ring strands apparently braided together.

flare Explosive event occurring in or near an active region on the Sun.

flatness problem One of two conceptual problems with the Standard Big Bang model, which is that there is no natural way to explain why the density of the universe is so close to the critical density.

fluidized ejecta The ejecta blankets around some Martian craters, which apparently indicate that the ejected material was liquid at the time the crater formed.

focus One of two special points within an ellipse, whose separation from each other indicate the eccentricity. In a bound orbit, objects move in ellipses about one focus.

forbidden line A spectral line seen in emission nebulae but not seen in laboratory experiments, because under laboratory conditions, collisions kick the electron in question into some other state before emission can occur.

force Action on an object that causes its momentum to change. The rate at which the momentum changes is numerically equal to the force.

fragmentation The breaking up of a large object into many smaller pieces (for example, as the result of high-speed collisions between planetesimals and protoplanets in the early solar system).

Fraunhofer lines The collection of over 600 absorption lines in the spectrum of the Sun, first categorized by Joseph Fraunhofer in 1812.

frequency The number of wave crests passing any given point per unit of time.

full Moon Phase of the Moon in which it appears as a complete circular disk in the sky.

fusion Mechanism of energy generation in the core of the Sun, in which light nuclei are combined, or fused, into heavier ones, releasing energy in the process.

S

S0 galaxy Galaxy which shows evidence of a thin disk and a bulge, but which has no spiral arms and contains little or no gas.

SB0 galaxy S0-type galaxy whose disk shows evidence of a bar.

scarp Surface feature on Mercury believed to be the result of cooling and shrinking of the crust, forming a wrinkle on the face of the planet.

Schwarzschild radius The distance from the center of an object such that, if all the mass compressed within that region, the escape velocity would equal the speed of light. Once a stellar remnant collapses within this radius, light cannot escape and the object is no longer visible.

scientific method The set of rules used to guide science, based on the idea that scientific laws be continually tested, and modified or replaced if found inadequate.

seasonal cap Portion of Martian polar ice caps that is subject to seasonal variations, growing and shrinking once each Martian year.

seasons Changes in average temperature and length of day that result from the tilt of Earth's (or any planet's) axis with respect to the plane of its orbit.

secondary atmosphere The chemicals that composed Earth's atmosphere after the planet's formation, once volcanic activity outgassed chemicals from the interior.

seeing A term used to describe the ease with which good telescopic observations can be made from Earth's surface, given the blurring effects of atmospheric turbulence.

seeing disk Roughly circular region on a detector over which a star's pointlike images is spread, due to atmospheric turbulence.

seismic wave A wave that travels outward from the site of an earthquake through the Earth.

semi-major axis One half of the major axis of an ellipse. The semi-major axis is the way in which the size of an ellipse is usually quantified.

semi-major axisx Type of active galaxy whose emission comes from a very small region within the nucleus of an otherwise normal-looking spiral system.

Seyfert galaxy Type of active galaxy whose emission comes from a very small region within the nucleus of an otherwise normal-looking sprial system.

shepherd satellite Satellite whose gravitational effect on a ring helps preserve the ring's shape. Examples are two satellites of Saturn, Prometheus and Pandora, whose orbits lie on either side of the F ring.

shield volcano A volcano produced by repeated nonexplosive eruptions of lava, creating a gradually sloping, shield-shaped low dome. Often contains a caldera at its summit.

shock wave Wave of matter, which may be generated by a star, which pushes material outward into the surrounding molecular cloud. The material tends to pile up, forming a rapidly-expanding shell of dense gas.

sidereal day The time needed for a star on the celestial sphere to make one complete rotation in the sky.

sidereal month Time required for the Moon to complete one trip around the celestial sphere.

sidereal year The time required for the constellations to complete once cycle around the sky and return to their starting points, as seen from a given point on Earth.

singularity A point in the universe where the density of matter and the gravitational field are infinite, such as at the center of a black hole.

solar constant The amount of solar energy reaching Earth per unit area per unit time, approximately 1400 W/m^2.

solar core The region at the center of the Sun, with a radius of nearly 200,000 km, where powerful nuclear reactions generate the Sun's energy output.

solar cycle The 22-year period that is needed for both the average number of spots and the Sun's magnetic polarity to repeat themselves. The Sun's polarity reverses on each new 11-year sunspot cycle.

solar day The period of time between the instant when the Sun is directly overhead (i.e. at noon) to the next time it is directly overhead.

solar eclipse Celestial event during which the new Moon passes directly between the Earth and Sun, temporarily blocking the Sun's light.

solar interior The region of the Sun between the solar core and the photosphere.

solar maximum The starting point of the sunspot cycle, during which only a few spots are seen. They are generally confined to narrow regions, one in each hemisphere, at about 25-30 degrees latitude.

solar minimum The starting point of the sunspot cycle, during which only a few spots are seen. They are generally confined to narrow regions, one in each hemisphere, at about 25&151;30 degrees latitude.

solar nebula The swirling gas surrounding the early Sun during the epoch of solar system formation, also referred to as the primitive solar system.

solar neutrino problem The discrepancy between the theoretically predicted numbers of neutrinos streaming from the Sun as a result of fusion reactions in the core and the numbers actually observed. The observed number of neutrinos is only about half the predicted number.

solar system The Sun and all the bodies that orbit it—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto, their moons, the asteroids, and the comets.

solar wind An outward flow of fast-moving charged particles from the Sun.

south celestial pole Point on the celestial sphere directly above the Earth's south pole.

spectral class Classification scheme, based on the strength of stellar spectral lines, which is an indication of the temperature of a star.

spectrometer Instrument used to produce detailed spectra of stars. Usually, a spectrograph records a spectrum on a photographic plate, or more recently, in electronic form on a computer.

spectroscope Instrument used to view a light source so that it is split into its component colors.

spectroscopic binary A binary-star system which from Earth appears as a single star, but whose spectral lines show back-and-forth Doppler shifts as two stars orbit one another.

spectroscopic parallax Method of determining the distance to a star by measuring its temperature and then determining its absolute brightness by comparing with a standard H—R diagram. The absolute and apparent brightnesses of the star give the star's distance from Earth.

spectroscopy The study of the way in which atoms absorb and emit electromagnetic radiation. Spectroscopy allows astronomers to determine the chemical composition of stars.

speed of light The fastest possible speed, according to the currently known laws of physics. Electromagnetic radiation exists in the form of waves or photons moving at the speed of light.

spin-orbit resonance State that a body is said to be in if its rotation period and its orbital period are related in a simple way.

spiral arm Distribution of material in a galaxy in a pinwheel-shaped design apparently emanating from near the galactic center.

spiral density wave (i) A wave of matter formed in the plane of planetary rings, similar to ripples on the surface of a pond, which wrap around the rings forming spiral patterns similar to grooves in a record disk. Spiral density waves can lead to the appearance of ringlets. (ii) A proposed explanation for the existence of galactic spiral arms, in which coiled waves of gas compression move through the galactic disk, triggering star formation.

spiral galaxy Galaxy composed of a flattened, star-forming disk component which may have spiral arms and a large central galactic bulge.

standard candle Any object with an easily recognizable appearance and known luminosity, which can be used in estimating distances. Supernovae, which all have the same peak luminosity (depending on type) are good examples of standard candles and are used to determine distances to other galaxies.

Standard Solar Model A self-consistent picture of the Sun, developed by incorporating the important physical processes that are believed to be important in determining the Sun's internal structure, into a computer program. The results of the program are then compared with observations of the Sun, and modifications are made to the model. The Standard Solar Model, which enjoys widespread acceptance, is the result of this process.

star A glowing ball of gas held together by its own gravity and powered by nuclear fusion in its core.

star cluster A grouping of anywhere from a dozen to a million stars which formed at the same time from the same cloud of interstellar gas. Stars in clusters are useful to aid our understanding of stellar evolution because they are all roughly the same age and chemical composition, and lie at roughly the same distance from Earth.

starburst galaxy Galaxy in which a violent event, such as near-collision, has caused a sudden, intense burst of star formation in the recent past.

Stefan's law Relation that gives the total energy emitted per square centimeter of its surface per second by an object of a given temperature. Stefan's law shows that the energy emitted increases rapidly with an increase in temperature, proportional to the temperature raised to the fourth power.

stellar nucleosynthesis The formation of heavy elements by the fusion of lighter nucleii in the hearts of stars. Except for hydrogen and helium, all other elements in our universe result from stellar nucleosynthesis.

stellar occultation The dimming of starlight produced when a solar system object such as a planet, moon, or ring, passes directly in front of a star.

stratosphere The portion of Earth's atmosphere lying above the troposphere, extending up to an altitude of 40 to 50 km.

strong nuclear force Short-range force responsible for binding atomic nuclei together. The strongest of the four fundamental forces of nature.

subgiant branch The section of the evolutionary track of a star that corresponds to changes that occur just after hydrogen is depleted in the core, and core hydrogen burning ceases. Shell hydrogen burning heats the outer layers of the star, which causes a general expansion of the stellar envelope.

summer solstice Point on the ecliptic where the Sun is at its northernmost point above the celestial equator, occurring on or near June 21.

sunspot An Earth-sized dark blemish found on the surface of the Sun. The dark color of the sunspot indicates that it is a region of lower temperature than its surroundings.

sunspot cycle The fairly regular pattern that the number and distribution of sunspots follows, in which the average number of spots reaches a maximum every 11 or so years, then falls off to almost zero.

supercluster Grouping of several clusters of galaxies into a larger, but not necessarily gravitationally bound, unit.

supergiant A star with a radius between 100 and 1000 times that of the Sun.

supergranulation Large-scale flow pattern on the surface of the Sun, consisting of cells measuring up to 30,000 km across, believed to be the imprint of large convective cells deep in the solar interior.

supernova Explosive death of a star, caused by the sudden onset of nuclear burning (type I), or an enormously energetic shock wave (type II). One of the most energetic events of the universe, a supernova may temporarily outshine the rest of the galaxy in which it resides.

supernova remnant The scattered glowing remains from a supernova that occurred in the past. The Crab Nebula is one of the best-studied supernova remnants.

synchrotron radiation Type of nonthermal radiation caused by high-speed charged particles, such as electrons, as they are accelerated in a strong magnetic field.

synchronous orbit State of an object when its period of rotation is exactly equal to its average orbital period. The Moon is in a synchronous orbit, and so presents the same face toward Earth at all times.

synodic month Time required for the Moon to complete a full cycle of phases.

A

A ring One of three Saturnian rings visible from Earth. The A ring is farthest from the planet and is separated from the B ring by the Cassini division.

absolute brightness The apparent brightness a star would have if it were placed at a standard distance of 10 parsecs from Earth.

absolute magnitude The apparent magnitude a star would have if it were placed at a standard distance of 10 parsecs from Earth.

absorption line Dark line in an otherwise continuous bright spectrum, where light within one narrow frequency range has been removed.

acceleration The rate of change of velocity of a moving object.

accretion Gradual growth of bodies, such as stars or planets, by the accumulation of gas or other, smaller, bodies.

accretion disk Flat disk of matter spiraling down onto the surface of a neutron star or black hole. Often, the matter originated on the surface of a companion star in a binary system.

active galaxies The most energetic galaxies, which can emit hundreds or thousands of times more energy per second than the Milky Way.

active optics Collection of techniques now being used to increase the resolution of ground-based telescopes. Minute modifications are made to the overall configuration of an instrument as its temperature and orientation change, to maintain the best possible focus at all times.

active region Region of the photosphere of the Sun surrounding a sunspot group, which can erupt violently and unpredictably. During sunspot maximum, the number of active regions is also a maximum.

active Sun The unpredictable aspects of the Sun's behavior, such as sudden explosive outbursts of radiation in the form of prominences and flares.

adaptive optics Technique used to increase the resolution of a telescope by deforming the shape of the mirror's surface under computer control while a measurement is being taken, to undo the effects of atmospheric turbulence.

amino acids Organic molecules which form the basis for building the proteins that direct metabolism in living creatures.

amplitude The maximum deviation of a wave above or below the zero point.

angular momentum problem The fact that the Sun, which contains nearly all of the mass of the solar system, accounts for just 0.3 percent of the total angular momentum of the solar system. This is an aspect of the solar system that any acceptable formation theory must address.

angular resolution The ability of a telescope to distinguish between adjacent objects in the sky.

annular eclipse annular eclipse Solar eclipse occurring at a time when the Moon is far enough away from the Earth that it fails to cover the disk of the Sun completely, leaving a ring of sunlight visible around its edge.

aphelion The point on the elliptical path of an object in orbit about the Sun that is most distant from the Sun

Apollo asteroid See Earth-crossing asteroid.

apparent brightness The brightness that a star appears to have, as measured by an observer on Earth.

apparent magnitude The apparent brightness of a star, expressed using the magnitude scale.

arc degree Unit of angular measure. There are 360 arc degrees in one complete circle.

association Small grouping of (typically 100 or less) stars, spanning up to a few tens of parsecs across, usually rich in very young stars.

asteroid One of thousands of very small members of the solar system orbiting the Sun between the orbits of Mars and Jupiter. Asteroids are often referred to as "minor planets."

asteroid belt Region of the solar system, between the orbits of Mars and Jupiter, in which most asteroids are found.

asthenosphere Layer of Earth's interior, just below the lithosphere, over which the surface plates slide.

astronomical unit (A.U.) The average distance of Earth from the Sun. Precise radar measurements yield a value for the A.U. of 149,603,500 km.

astronomy Branch of science dedicated to the study of everything in the universe that lies above Earth's atmosphere.

asymptotic giant branch Path on the H-R diagram corresponding to the changes that a star undergoes after helium burning ceases in the core. At this stage, the carbon core shrinks and drives the expansion of the envelope, and the star becomes a swollen red giant for a second time.

atmosphere Layer of gas confined close to a planet's surface by the force of gravity.

atom Building block of matter, composed of positively charged protons and neutral neutrons in the nucleus, surrounded by negatively charged electrons.

aurora Event which occurs when atmospheric molecules are excited by incoming charged particles from the solar wind, then emit energy as they fall back to their ground states. Aurorae generally occur at high latitudes, near the north and south magnetic poles.

autumnal equinox Date on which the Sun crosses the celestial equator moving southward, occurring on or near September 22.

N

nebula General term used for any "fuzzy" patch on the sky, either light or dark.

nebular theory One of the earliest models of solar system formation, dating back to Descartes, in which a large cloud of gas began to collapse under its own gravity to form the Sun and planets.

neutrino Virtually massless and chargeless particle that is one of the products of fusion reactions in the Sun. Neutrinos move at close to the speed of light, and interact with matter hardly at all.

neutrino oscillations Possible solution to the solar neutrino problem, in which the neutrino has a very tiny mass. In this case, the correct number of neutrinos can be produced in the solar core, but on their way to Earth, some can "oscillate," or become transformed into other particles, and thus go undetected.

neutron An elementary particle with roughly the same mass as a proton, but which is electrically neutral. Along with protons, neutrons form the nuclei of atoms.

neutron capture The primary mechanism by which very massive nuclei are formed in the violent aftermath of a supernova. Instead of fusion of like nuclei, heavy elements are created by the addition of more and more neutrons to existing nuclei.

neutron star A dense ball of neutrons that remains at the core of a star after a supernova explosion has destroyed the rest of the star. Typical neutron stars are about 20 km across, and contain more mass than the Sun.

new Moon Phase of the moon during which none of the lunar disk is visible.

Newtonian mechanics The basic laws of motion, postulated by Newton, which are sufficient to explain and quantify virtually all of the complex dynamical behavior found on Earth and elsewhere in the universe.

Newtonian telescope A reflecting telescope in which incoming light is intercepted before it reaches the prime focus and is deflected into an eyepiece at the side of the instrument.

north celestial pole Point on the celestial sphere directly above the Earth's north pole.

nova A star that suddenly increases in brightness, often by a factor of as much as 10,000, then slowly fades back to its original luminosity. A nova is the result of an explosion on the surface of a white dwarf star, caused by matter falling onto its surface from the atmosphere of a binary companion.

nuclear fusion Mechanism of energy generation in the core of the Sun, in which light nuclei are combined, or fused, into heavier ones, releasing energy in the process.

nucleotide base An organic molecule, the building block of genes that pass on hereditary characteristics from one generation of living creatures to the next.

nucleus Dense, central region of an atom, containing both protons and neutrons, and orbited by one or more electrons. The solid region of ice and dust that composes the central region of the head of a comet.

I

image The optical representation of an object produced when light from the object is reflected or refracted by a mirror or lens.

inertia The tendency of an object to continue in motion at the same speed and in the same direction, unless acted upon by a force.

inflation Short period of unchecked cosmic expansion early in the history of the universe. During inflation, the universe swelled in size by a factor of about 1050.

infrared Region of the electromagnetic spectrum just outside the visible range, corresponding to light of a slightly longer wavelength than red light.

infrared telescope Telescope designed to detect infrared radiation. Many such telescopes are designed to be lightweight so that they can be carried above most of Earth's atmosphere by balloons, airplanes, or satellites.

inner core The central part of Earth's core, believed to be solid, and composed mainly of nickel and iron.

intensity A basic property of electromagnetic radiation that specifies the amount or strength of the radiation.

intercrater plains Regions on the surface of Mercury that do not show extensive cratering, but are relatively smooth.

interference The ability of two or more waves to interact in such a way that they either reinforce or cancel each other.

interferometer Collection of two or more telescopes working together as a team, observing the same object at the same time and at the same wavelength. The effective diameter of an interferometer is equal to the distance between its outermost telescopes.

interferometry Technique in widespread use to dramatically improve the resolution of radio and infrared maps. Several telescopes observe an object simultaneously, and a computer analyzes how the signals interfere with one another to reconstruct a detailed image of the field of view.

interplanetary space The space between the objects in the solar system.

interstellar dust Microscopic dust grains that populate the space between stars, having their origins in the ejected matter of long-dead stars.

interstellar medium The matter between stars, composed of two components, gas and dust, intermixed throughout all of space.

inverse-square law The law that a field follows if its strength decreases with the square of the distance. Fields that follow the inverse square law rapidly decrease in strength as the distance increases, but never quite reach zero.

Io plasma torus Doughnut-shaped region of energetic ionized particles, emitted by the volcanoes on Jupiter's moon Io, and swept up by Jupiter's magnetic field.

ion An atom that has lost one or more electrons.

ion tail Thin stream of ionized gas that is pushed away from the head of a comet by the solar wind. It extends directly away from the Sun. Often referred to as a plasma tail.

ionized State of an atom that has had at least one of its electrons removed.

ionosphere Layer in Earth's atmosphere above about 100 km where the atmosphere is significantly ionized, and conducts electricity.

irregular galaxy A galaxy which does not fit into any of the other major categories in the Hubble classification scheme.

isotopes Nuclei containing the same number of protons but different numbers of neutrons. Most elements can exist in several isotopic forms. A common example of an isotope is deuterium, which differs from normal hydrogen by the presence of an extra neutron in the nucleus.

isotropic Assumed property of the universe such that the universe looks the same in every direction.

isotropy Assumed property of the universe such that the universe looks the same in every direction.

M

Magellanic Clouds Two small irregular galaxies that are gravitationally bound to the Milky Way Galaxy.

magnetic field Field which accompanies any changing electric field, and governs the influence of magnetized objects on one another.

magnetosphere A zone of charged particles trapped by a planet's magnetic field, lying above the atmosphere.

magnitude scale A system of ranking stars by apparent brightness, developed by the Greek astronomer Hipparchus. Originally, the brightest stars in the sky were categorized as being of first magnitude, while the faintest stars visible to the naked eye were classified as sixth magnitude. The scheme has since been extended to cover stars and galaxies too faint to be seen by the unaided eye. Increasing magnitude means fainter stars, and a difference of 5 magnitudes corresponds to a factor of 100 in apparent brightness.

main sequence Well-defined band on the Hertzsprung—Russell diagram, on which most stars are found, running from the top left of the diagram to the bottom right.

main-sequence turnoff Special point on the Hertzsprung—Russell diagram for a cluster, indicative of the cluster's age. If all the stars in the cluster are plotted, the lower mass stars will trace out the main sequence up to the point where stars begin to evolve off the main sequence toward the red giant branch. The point where stars are just beginning to evolve off is the main-sequence turnoff.

mantle Layer of the Earth just interior to the crust.

mare Relatively dark-colored and smooth region on the surface of the Moon.

mass A measure of the total amount of matter contained within an object.

mass-luminosity relation The dependence of the luminosity of a main-sequence star on its mass. The luminosity increases roughly as the mass raised to the third power.

mass-radius relation The dependence of the radius of a main sequence star on its mass. The radius rises roughly in proportion to the mass.

mass-transfer binaries See semi-detached binary.

matter-dominated universe A universe in which the density of matter exceeds the density of radiation. The present-day universe is matter-dominated.

mesosphere Region of Earth's atmosphere lying between the stratosphere and the ionosphere, 50-80 km above Earth's surface.

meteor Bright streak in the sky, often referred to as a "shooting star," resulting from a small piece of interplanetary debris entering Earth's atmosphere and heating air molecules, which emit light as they return to their ground states.

meteor shower Event during which many meteors can be seen each hour, caused by the yearly passage of the Earth through the debris spread along the orbit of a comet.

meteorite Any part of a meteoroid that survives passage through the atmosphere and lands on the surface of Earth.

meteoroid Chunk of interplanetary debris prior to encountering Earth's atmosphere.

meteoroid swarm Pebble-sized cometary fragments dislodged from the main body, moving in nearly the same orbit as the parent comet.

micrometeoroids Relatively small chunks of interplanetary debris ranging from dust particle size to pebble-sized fragments.

Milky Way Galaxy The spiral galaxy in which the Sun resides. The disk of our Galaxy is visible in the night sky as the faint band of light known as the Milky Way.

millisecond pulsar A pulsar whose period indicates that the neutron star is rotating nearly 1000 times each second. The most likely explanation for these rapid rotators is that the neutron star has been spun up by drawing in matter from a companion star.

molecular cloud A cold, dense interstellar cloud which contains a high fraction of molecules. It is widely believed that the relatively high density of dust particles in these clouds plays an important role in the formation and protection of the molecules.

molecular cloud complex Collection of molecular clouds that spans as much as 50 parsecs and may contain enough material to make millions of Sun-sized stars.

molecule A tightly bound collection of atoms held together by the electromagnetic fields of the atoms. Molecules, like atoms, emit and absorb photons at specific wavelengths.

moon A small body in orbit about a planet.

U

ultraviolet Region of the electromagnetic spectrum, just outside the visible range, corresponding to wavelengths slightly shorter than blue light.

ultraviolet telescope A telescope that is designed to collect radiation in the ultraviolet part of the spectrum. The Earth's atmosphere is partially opaque to these wavelengths, so ultraviolet telescopes are put on rockets, balloons, or satellites to get high above most or all of the atmosphere.

umbra Central region of the shadow cast by an eclipsing body. The central region of a sunspot, which is its darkest and coolest part.

unbound An orbit which does not stay in a specific region of space, but where an object escapes the gravitational field of another. Typical unbound orbits are hyperbolic in shape.

universe The totality of all space, time, matter, and energy.

1.2 The Obvious View

How have we come to know the universe around us? How do we know the proper perspective sketched in Figure 1.5? Our study of the universe, the science of astronomy, begins by examining the sky.

CONSTELLATIONS IN THE SKY

Between sunset and sunrise on a clear night we can see some 3000 points of light. Include the view from the opposite side of Earth, and nearly 6000 stars are visible to the unaided eye. A natural human tendency is to see patterns and relationships between objects even when no true connection exists, and people long ago connected the brightest stars into configurations called **constellations**, which ancient astronomers named after mythological beings, heroes, and animals—whatever was important to them. Figure 1.6 shows a constellation especially prominent in the nighttime sky from October through March: the "hunter" named Orion. Orion was a mythical Greek hero famed, among other things, for his amorous pursuit of the Pleiades, the seven daughters of the giant Atlas. According to Greek mythology, in order to protect the Pleiades from Orion, the gods placed them among the stars, where Orion nightly stalks them across the sky. Many constellations have similarly fabulous connections with ancient lore.

Perhaps not surprisingly, the patterns seen have a strong cultural bias—the astronomers of ancient China saw mythical figures different from those seen by the ancient Greeks, the Babylonians, and the people of other cultures, even though they were all looking at the same stars in the night sky. Interestingly, though, different cultures often made the same basic *groupings* of stars, despite widely varying interpretations of what they saw. For example, the group of seven stars usually known in North America as "the Dipper" is known as "the Wagon" or "the Plough" in Western Europe. The ancient Greeks regarded these same stars as the tail of "the Great Bear," the Egyptians saw them as the leg of an ox, the Siberians as a stag. Some Native Americans saw two mythical brothers, others an ermine, others still a funeral procession.

Early astronomers had very practical reasons for studying the sky. Some constellations served as navigational guides. For example, the star Polaris, part of the Little Dipper, indicates north, and the near-constancy of its location in the sky, from hour to hour and night to night, has aided travelers for centuries. Other constellations served as primitive calendars to predict planting and harvesting seasons. For example, many cultures knew well that the appearance of certain stars on the horizon just before daybreak signaled the beginning of spring and the end of winter.

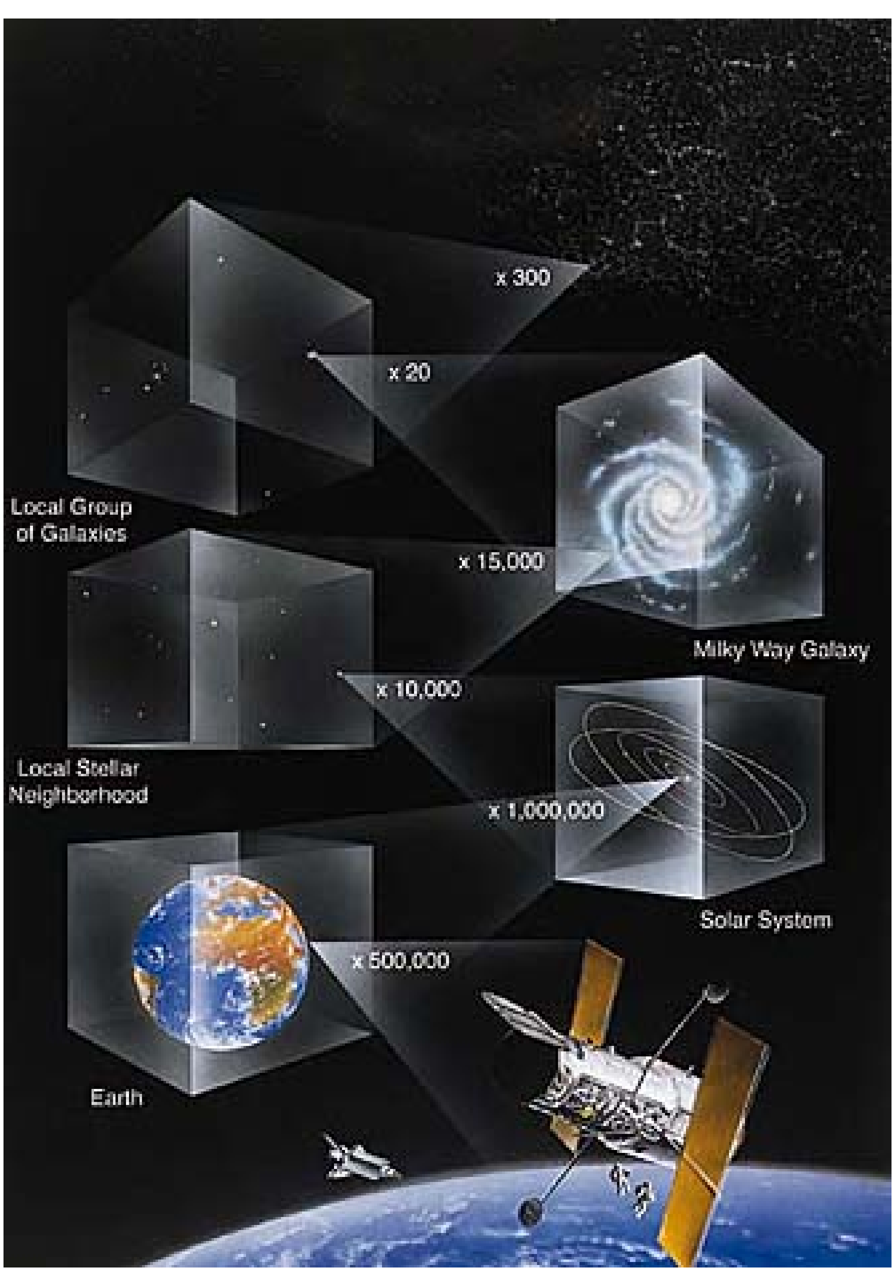


Figure 1.5 This artist's conception puts each of the previous figures in perspective. The bottom of this figure shows spacecraft (and astronauts) in Earth orbit, a view that widens progressively in each of the next five cubes drawn from bottom to top—Earth, the planetary system, the local neighborhood of stars, the Milky Way Galaxy, and the closest cluster of galaxies. The numbers indicate approximately the increase in scale between successive images.

In many societies, people came to believe that there were other benefits in being able to trace the regularly changing positions of heavenly bodies. The relative positions of stars and planets at a person's birth were carefully studied by *astrologers*, who used the data to make predictions about that person's destiny. Thus, in a sense, astronomy and astrology arose from the same basic impulse—the desire to "see" into the future—and, indeed, for a long time they were indistinguishable from one another. Today most people recognize that astrology is nothing more than an amusing diversion (although millions still study their horoscope in the newspaper every morning!). Nevertheless, the ancient astrological terminology—the names of the constellations and many terms used to describe the locations and motions of the planets, for example—is still used throughout the astronomical world.

Generally speaking, as illustrated in Figure 1.6(c) for the case of Orion, the stars that make up any particular constellation are not actually close to one another in space, even by astronomical standards. They merely are bright enough to observe with the naked eye and happen to lie in roughly the same direction in the sky as seen from Earth. Nevertheless, the constellations provide a convenient means for astronomers to specify large areas of the sky, much as geologists use continents, or politicians use voting precincts to identify certain localities on planet Earth. In all, there are 88 constellations, most of them visible from North America at some time during the year.

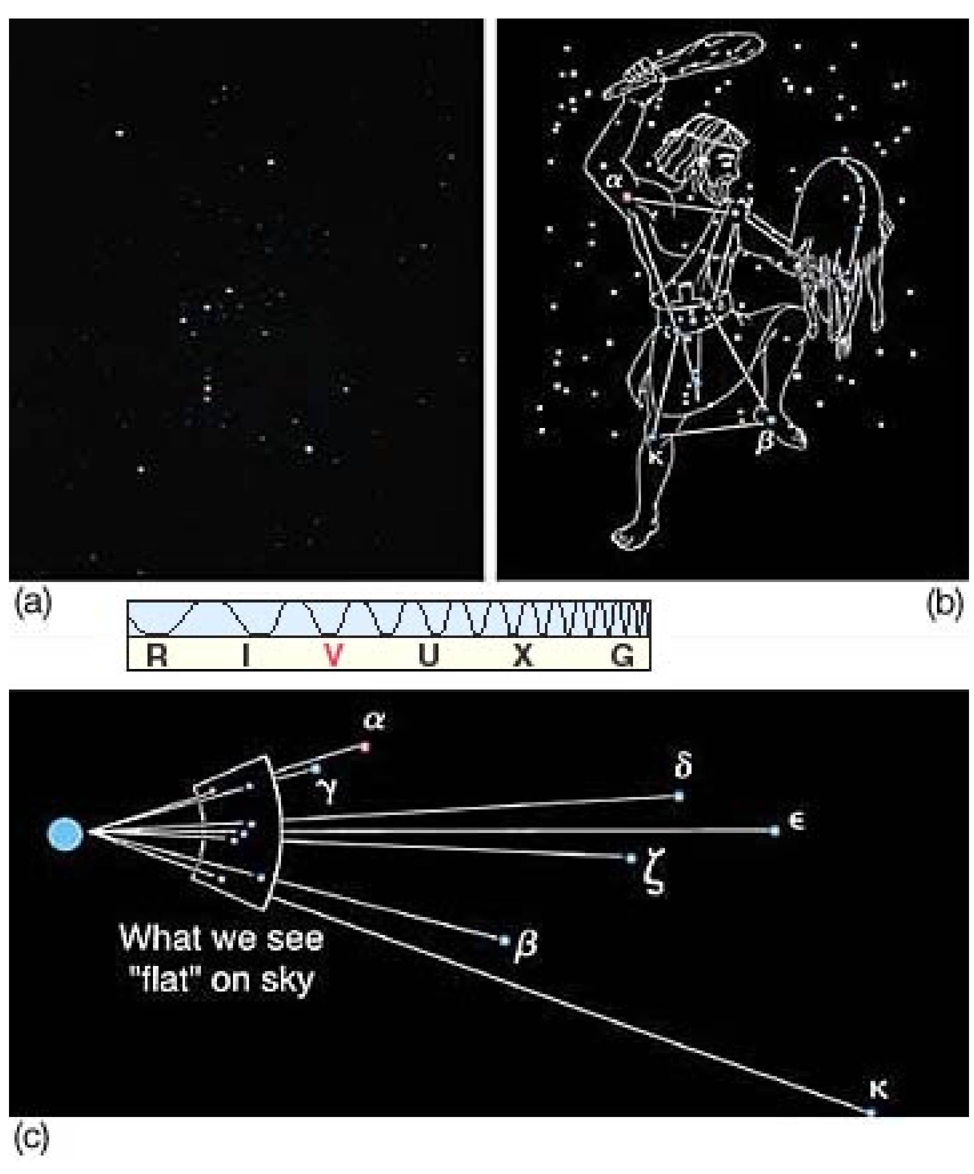


Figure 1.6 (a) A photograph of the group of bright stars that make up the constellation Orion. (b) The stars are connected to show the pattern visualized by the Greeks: the outline of a hunter. You can easily find this constellation in the winter sky by identifying the line of three bright stars in the hunter's "belt." (c) The true relationships among the stars, in three dimensions.

THE CELESTIAL SPHERE

1 Over the course of a night, the constellations seem to move smoothly across the sky from east to west, but ancient sky-watchers were well aware that the *relative* locations of stars remain unchanged as this nightly march takes place. It was natural for those observers to conclude that the stars must be firmly attached to a **celestial sphere** surrounding Earth—a canopy of stars resembling an astronomical painting on a heavenly ceiling. Figure 1.7 shows how early astronomers pictured the stars as moving with this celestial sphere as it turned around a fixed, unmoving Earth. Figure 1.8 shows how all stars appear to move in circles around a point very close to the star Polaris (better known as the Pole Star, or the North Star). To the ancients, this point represented the axis around which the entire celestial sphere turned.

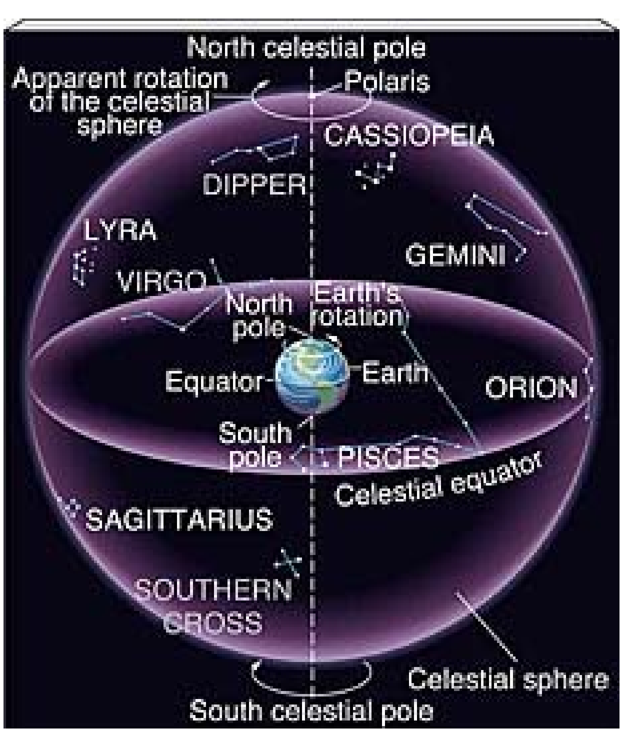


Figure 1.7 Planet Earth sits fixed at the hub of the celestial sphere, which contains all the stars. This is one of the simplest possible models of the universe, but it doesn't agree with all the facts that astronomers know about the universe.

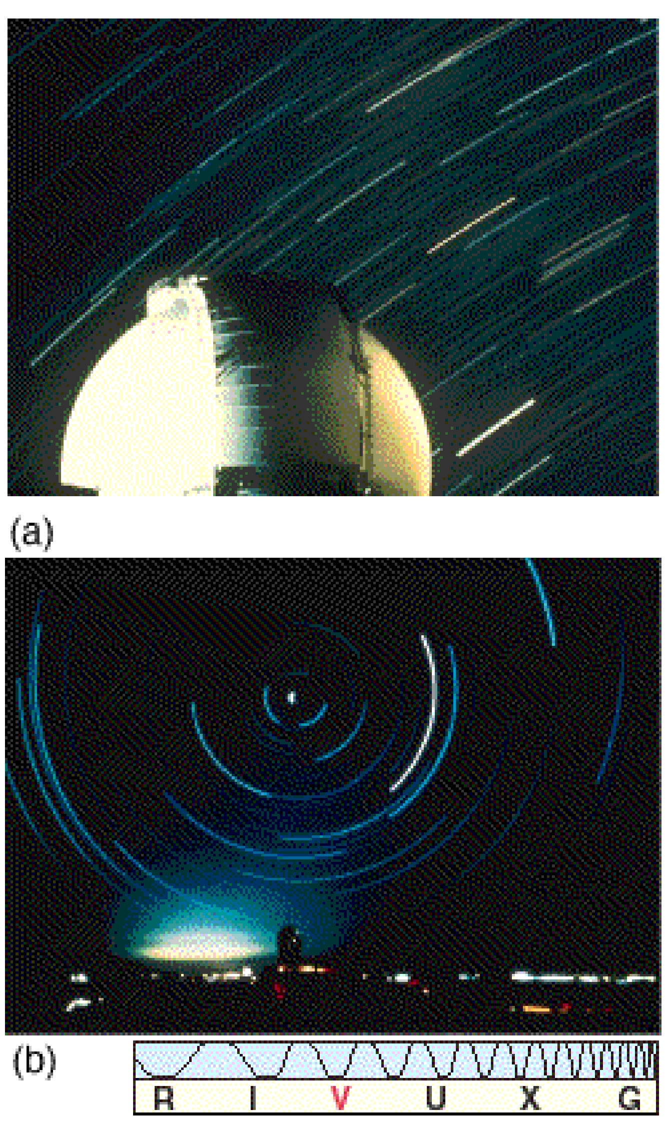


Figure 1.8 Time-lapse photographs of the northern sky. Each trail is the path of a single star across the nighttime sky. The duration of the exposure in (a) is about 1 hour, that in (b) is about 5 hours. (How can you tell that this is so?) The center of the concentric circles is near the north star, Polaris, whose short, bright arc is prominently visible in (b).

From our modern standpoint, the apparent motion of the stars is the result of the spin, or **rotation**, not of the celestial sphere but of Earth. Polaris indicates the direction—due north—in which Earth's rotation axis points. Even though we now know that the celestial sphere is an incorrect description of the heavens, we still use the idea as a convenient fiction that helps us visualize the positions of stars in the sky. The point where Earth's axis intersects the celestial sphere in the Northern Hemisphere is known as the **north celestial pole**, and it is directly above Earth's North Pole. In the Southern Hemisphere, the extension of Earth's axis in the opposite direction defines the **south celestial pole**, directly above Earth's South Pole. Midway between the north and south celestial poles lies the **celestial equator**, representing the intersection of Earth's equatorial plane with the celestial sphere. These parts of the celestial sphere are marked on Figure 1.7.

When discussing the locations of stars "on the sky," astronomers naturally talk in terms of *angular* positions and separations. *More Precisely 1-1* presents some basic information on angular measure. *More Precisely 1-2* discusses in more detail the system of coordinates used to specify stellar positions.

PREVIOUS NEXT CHAPTER REVIEW