2 THE COPERNICAN REVOLUTION

The Birth of Modern Science

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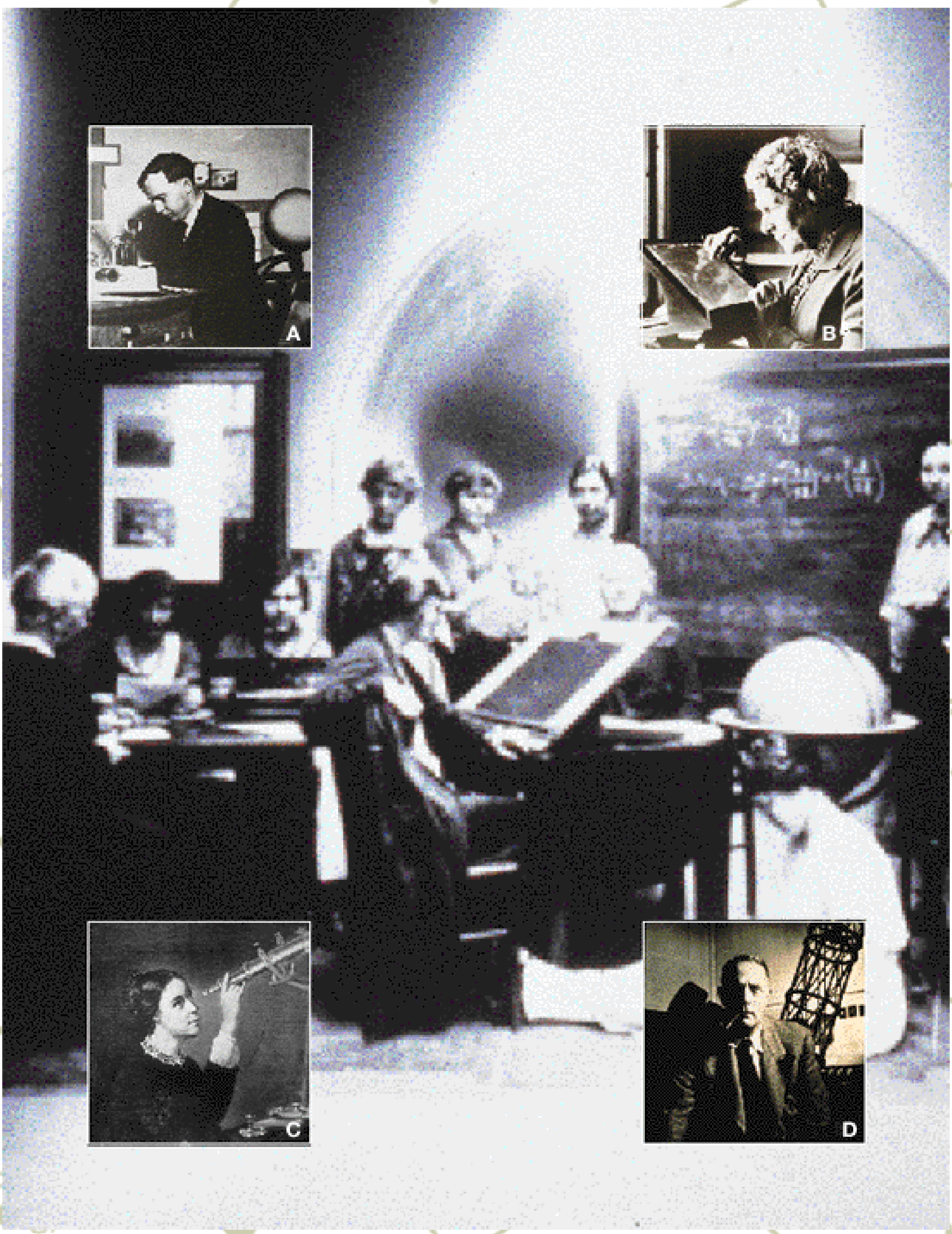

(Background) In an early twentieth-century classroom at Radcliffe College, as at other schools, astronomy came into its own as a viable and important subject.

(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

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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.

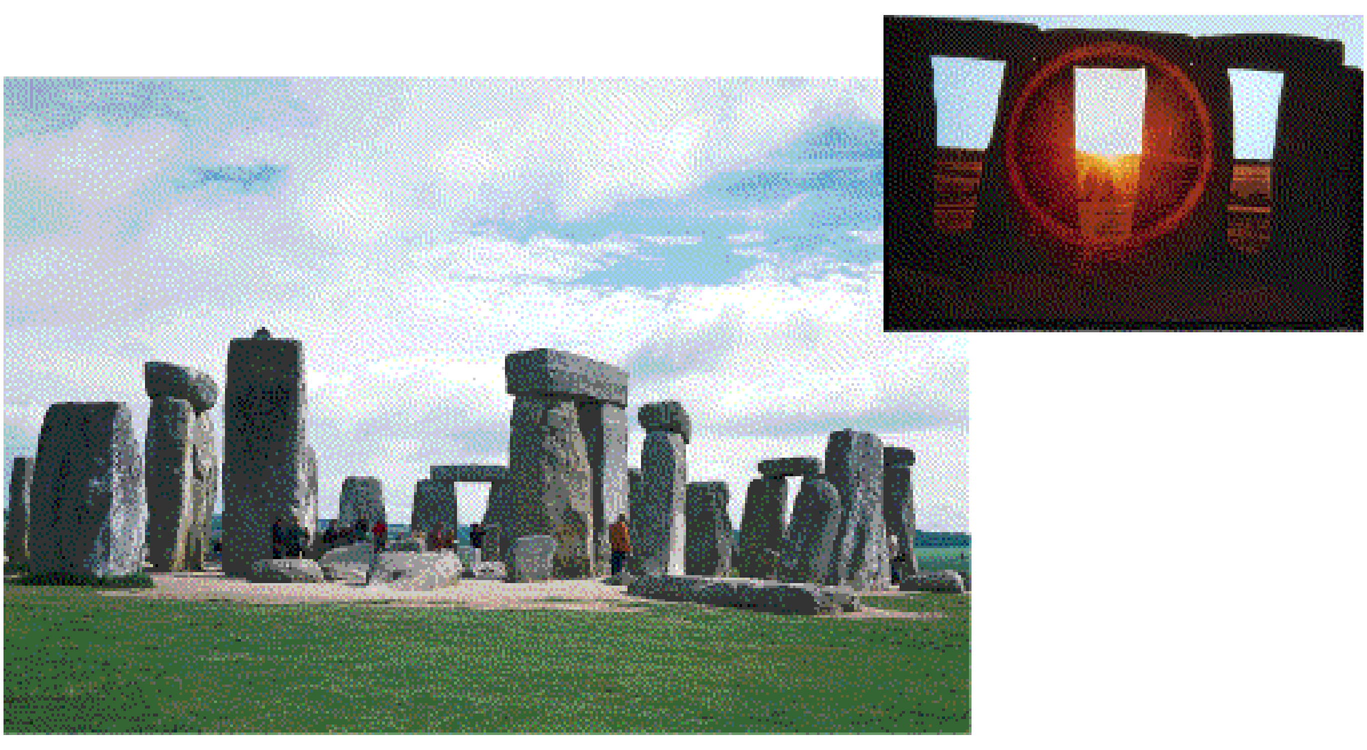


Figure 2.1 *Stonehenge was probably constructed as a primitive calendar and almanac. The fact that the largest stones were carried to the site from many miles away attests to the importance of this structure to its Stone Age builders. The inset shows sunrise at Stonehenge on the summer solstice. As seen 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**.

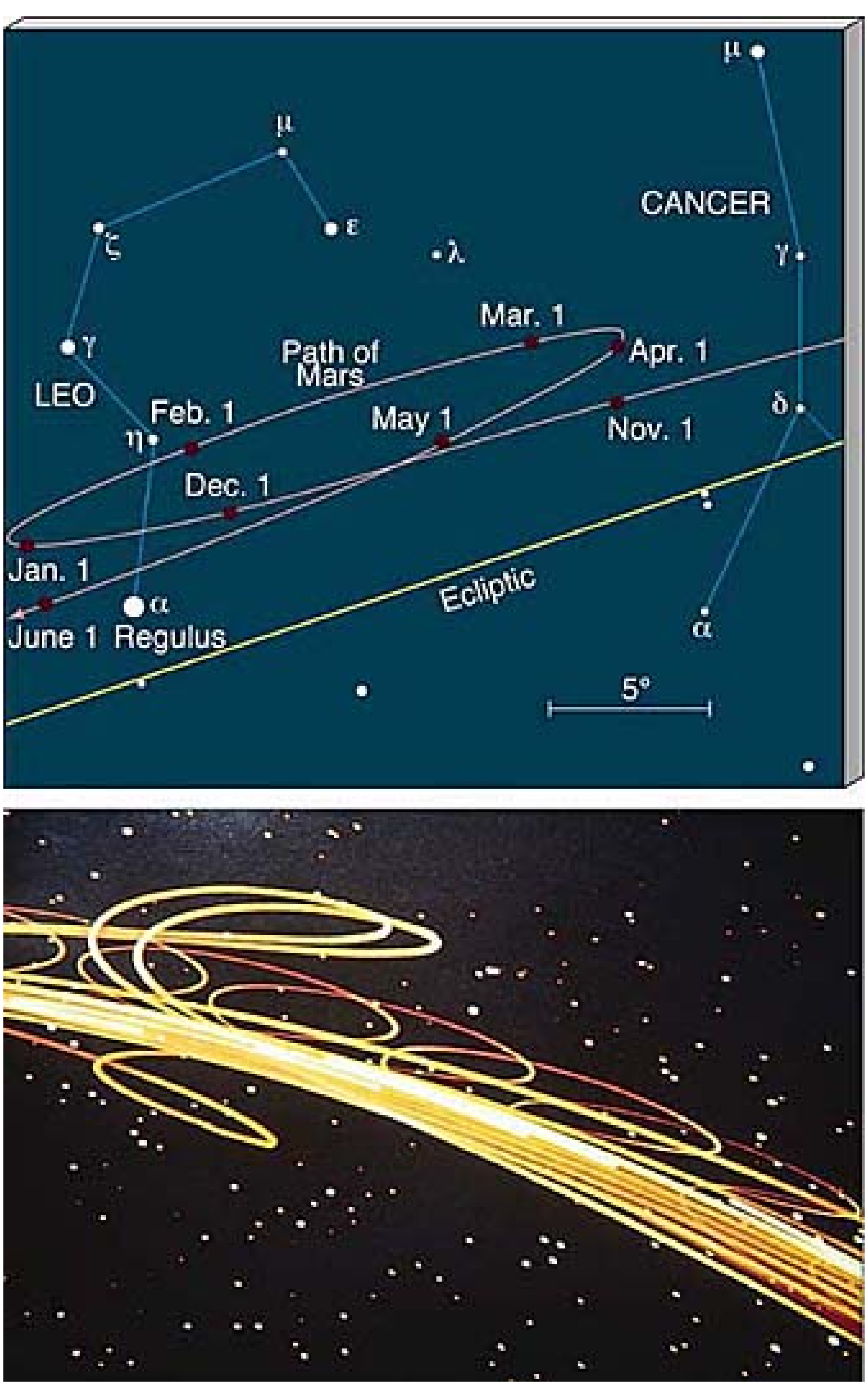


Figure 2.4 *Most of the time, planets move from west to east relative to the background stars. Occasionally, however, they change direction and temporarily undergo retrograde motion before looping back. The art above shows an actual retrograde loop in the motion of the planet Mars. The inset above depicts 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.

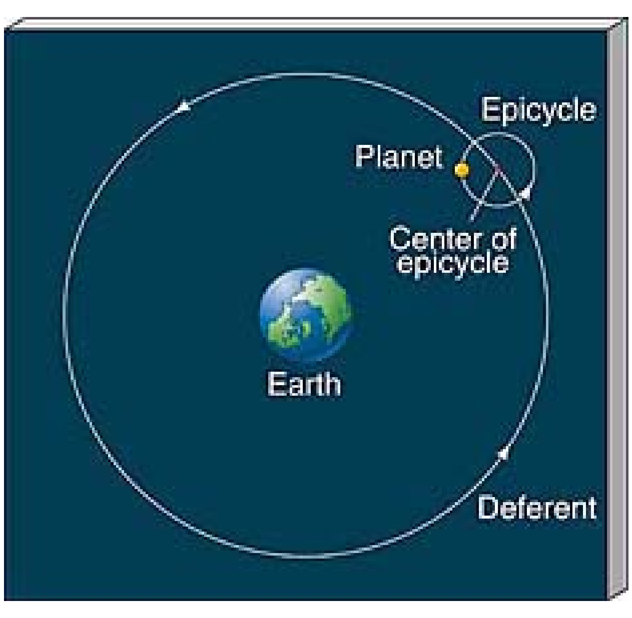


Figure 2.5 *In the geocentric model of the solar system, the observed motions of the planets made it impossible to assume that they moved on simple circular paths around Earth. Instead, each planet was thought to follow a small circular orbit (the epicycle) about an imaginary point that itself traveled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

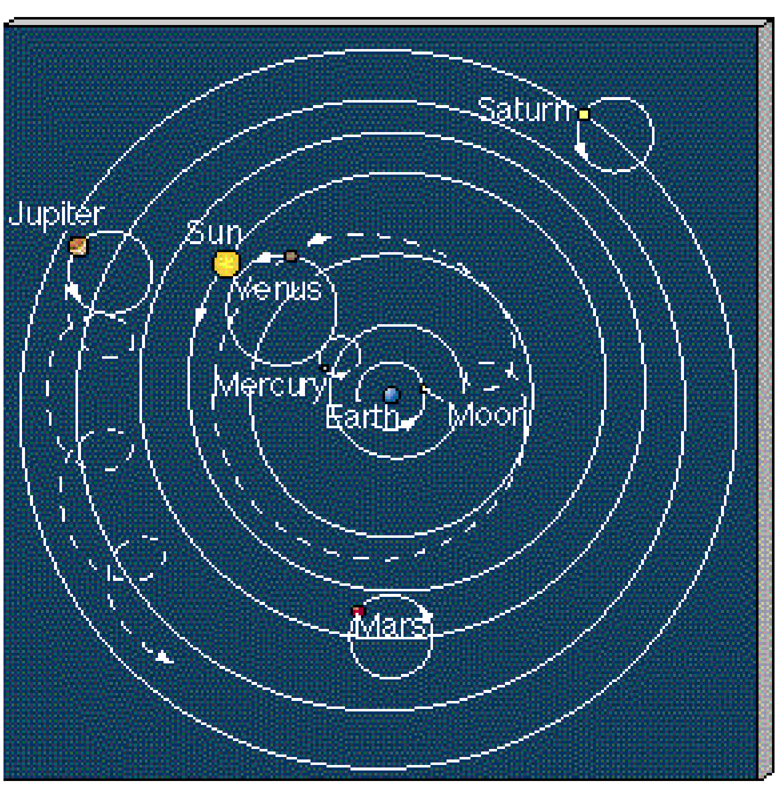


Figure 2.6 *The basic features, drawn roughly to scale, of the geocentric model of the inner solar system that enjoyed widespread popularity prior to the Renaissance. To avoid confusion, we have drawn partial paths (dashed) of only two planets, Venus and Jupiter.*

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*.

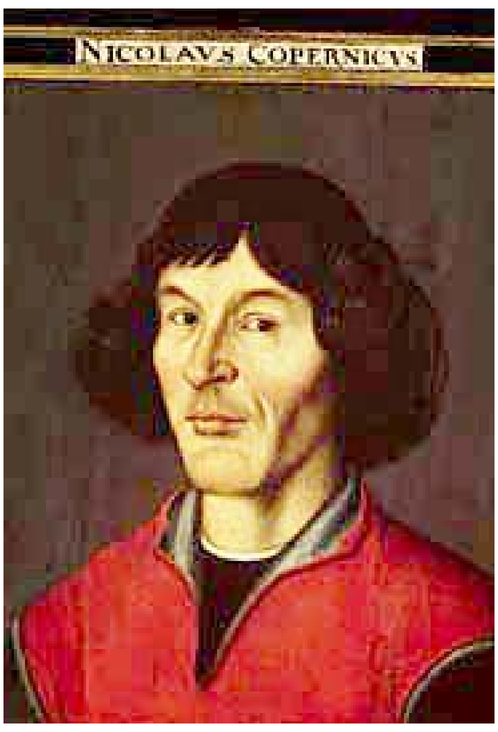


Figure 2.7 *Nicholas Copernicus (1473–1543).*

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.

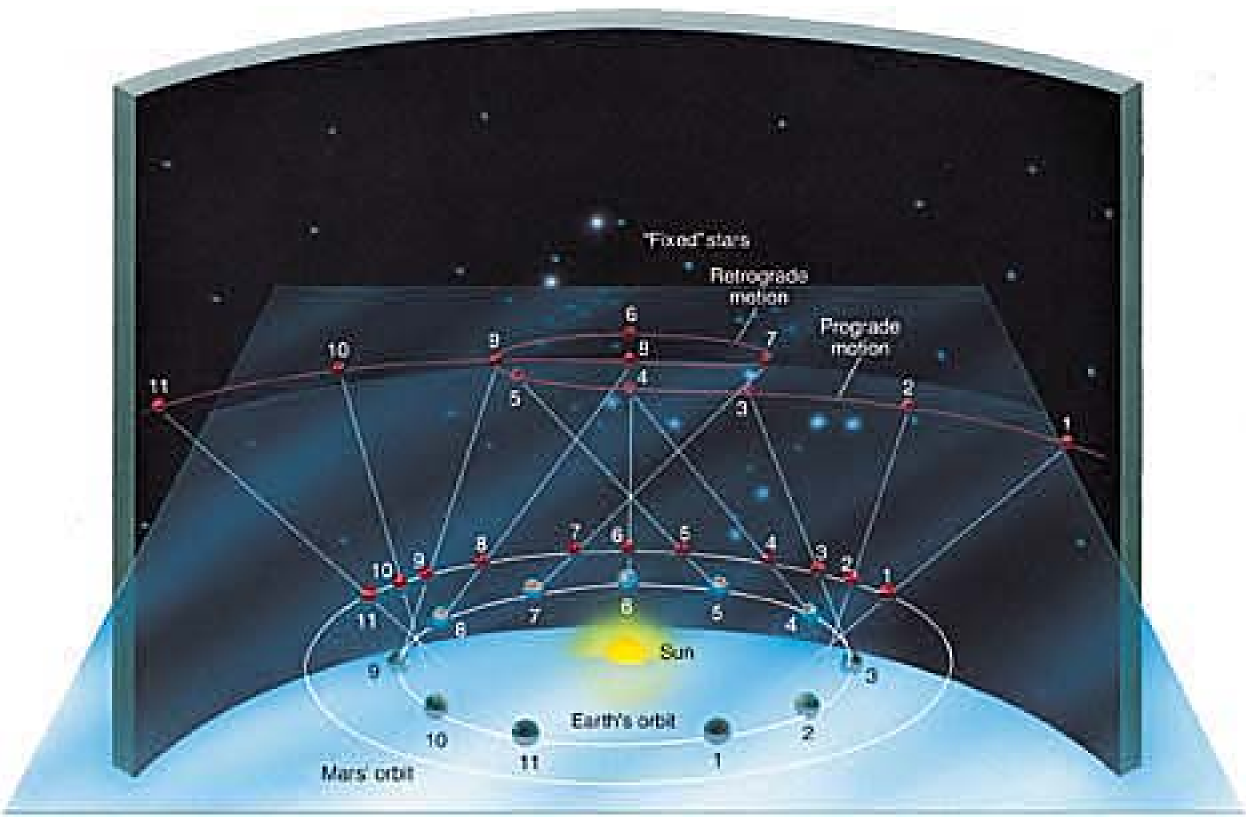


Figure 2.8 *The Copernican model of the solar system explains the varying brightnesses of the planets, something the Ptolemaic system largely ignored. Here, for example, when Earth and Mars are relatively close to each other in their respective orbits (as at position 6), Mars seems brighter; when farther 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.

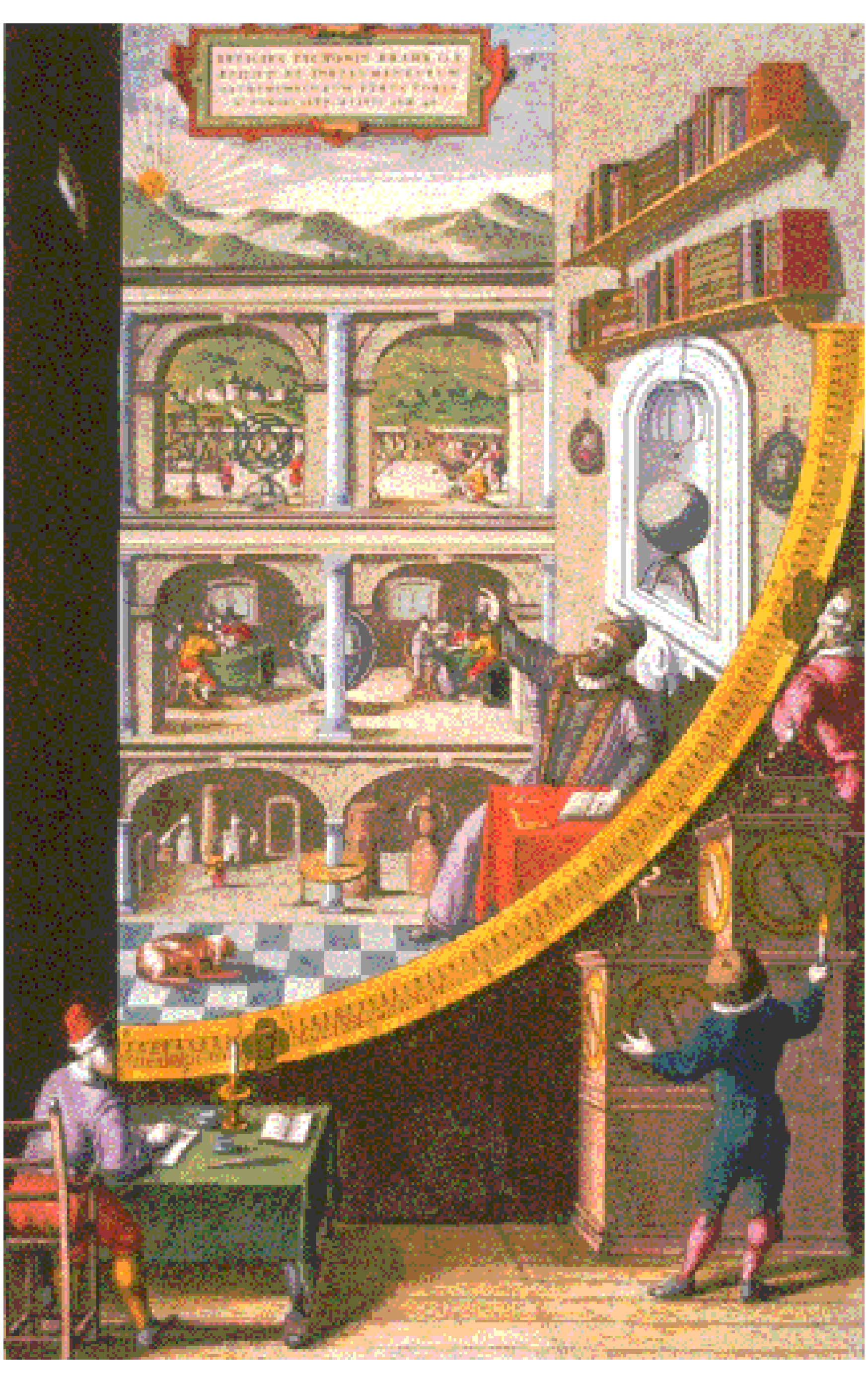


Figure 2.10 Tycho Brahe in his observatory Uraniborg, on the island of Hveen, in Denmark.

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.

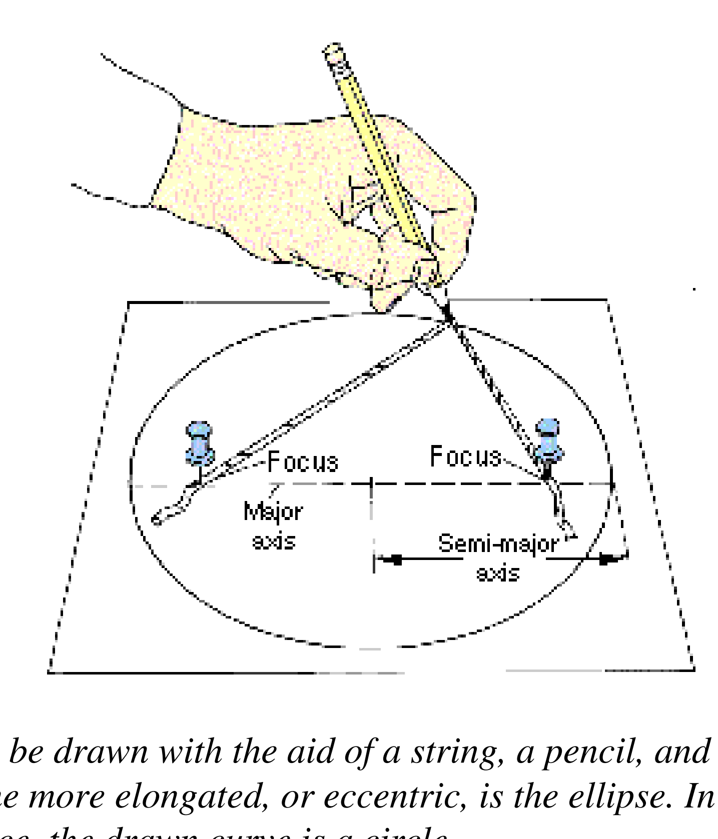


Figure 2.11 Any ellipse can be drawn with the aid of a string, a pencil, and two thumbtacks. The wider the separation of the foci, the more elongated, or eccentric, is the ellipse. In the special case where the two foci are at the same place, the drawn curve is a circle.

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.

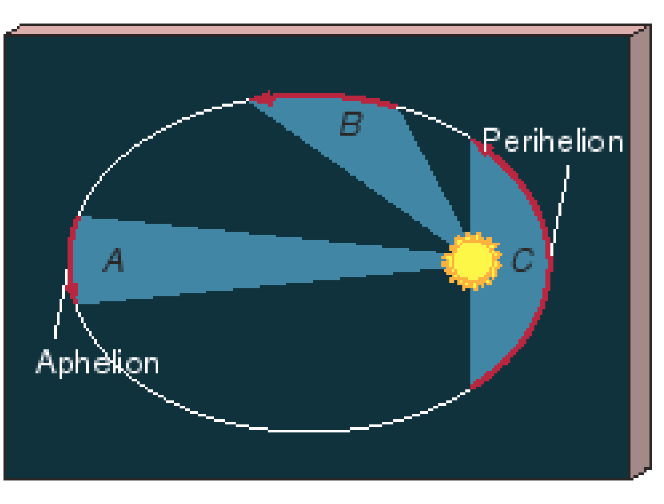


Figure 2.12 A diagram illustrating Kepler's second law: Equal areas are swept out in equal intervals of time. The three shaded areas (A, B, and C) are equal. Note that an object would travel the length of each of the three arrows in the same amount of time. Therefore, planets move faster when closer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

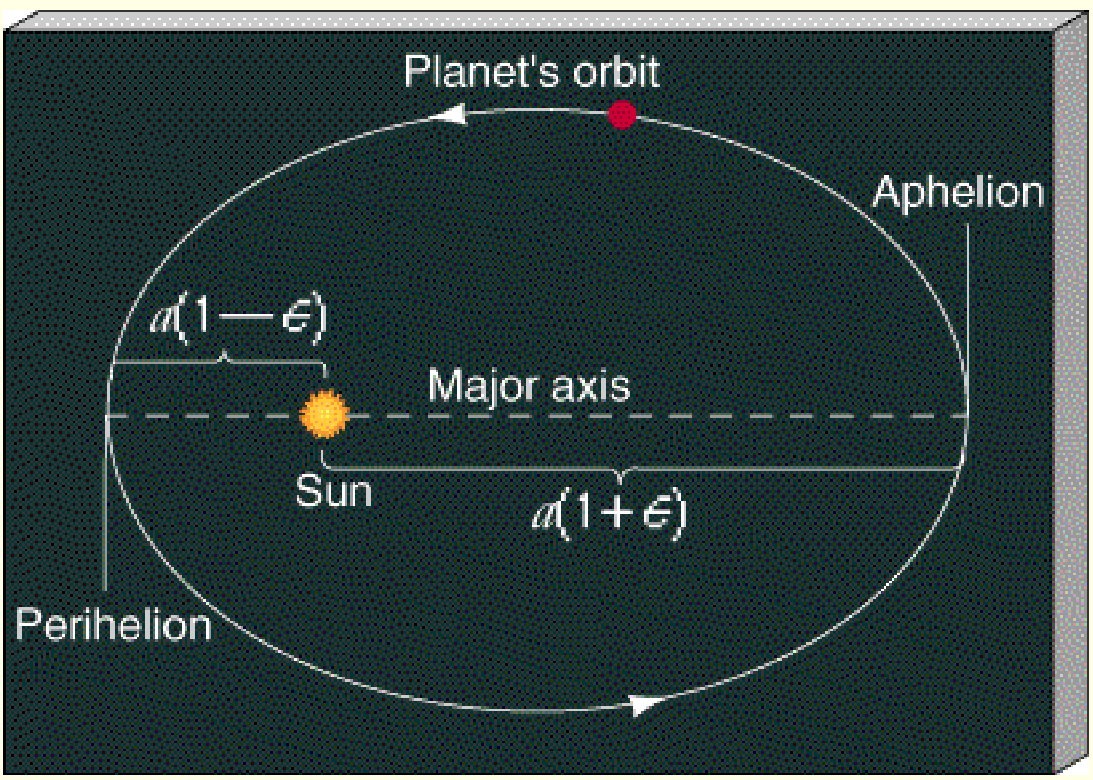
MORE PRECISELY 2-1 Some Properties of Planetary Orbits

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 $400 \times (1—0.5) = 200$ million km and $400 \times (1 + 0.5) = 600$ 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.

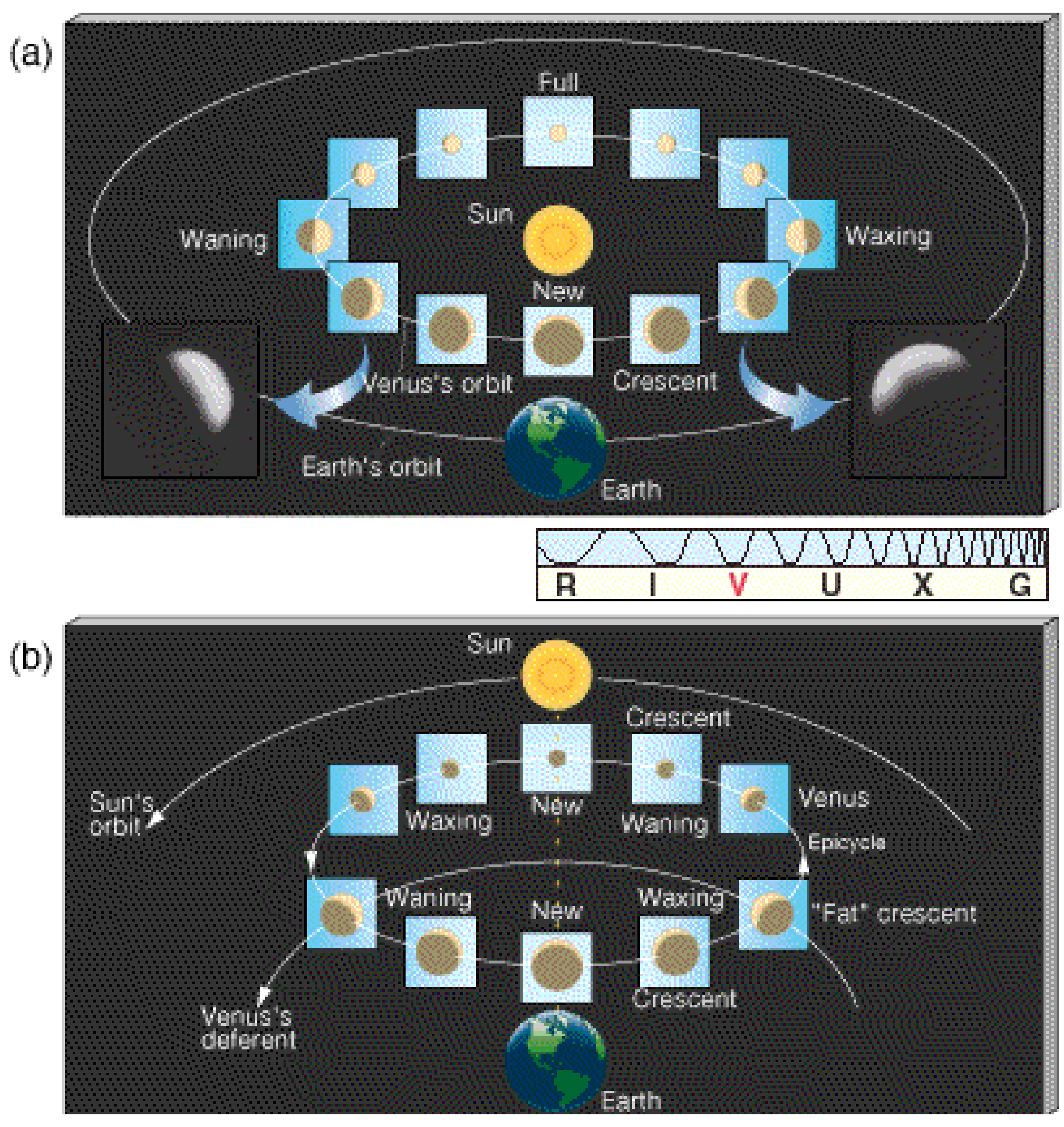


Figure 2.14 (a) The phases of Venus, rendered at different points in the planet's orbit. If Venus orbits the Sun and is closer to the Sun than is Earth, as Copernicus maintained, then Venus should display phases, much as our Moon does. As shown here, when directly between Earth and the Sun, Venus's unlit 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.

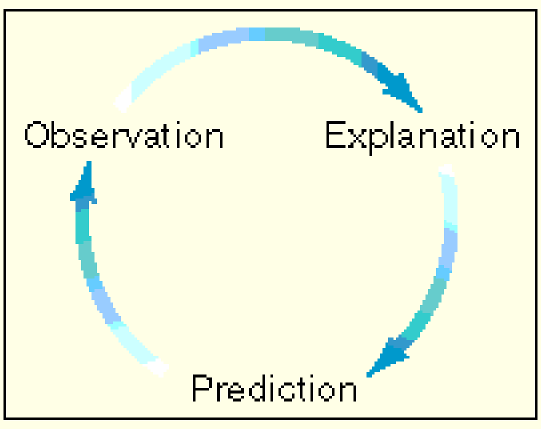
Notice, incidentally, that there is no "end point" to the process depicted in the figure. A theory can be invalidated by a single wrong prediction, but no amount of observation or experimentation can ever prove it correct. Theories simply become more and more widely accepted as their predictions are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

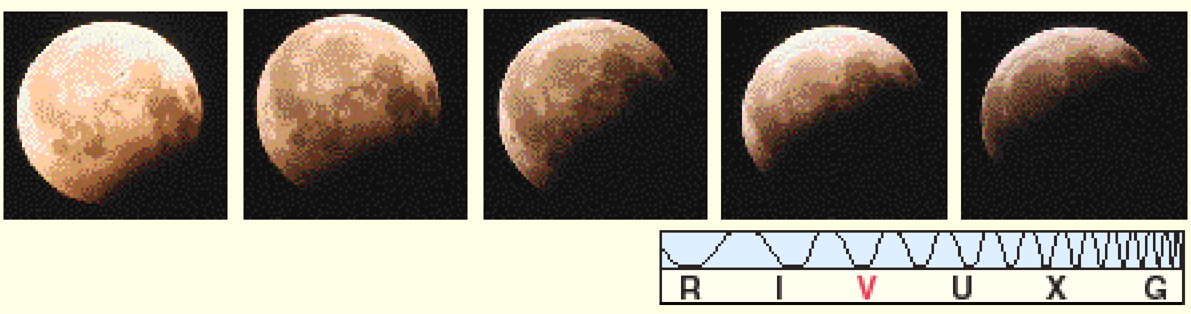
In astronomy we are rarely afforded the luxury of performing experiments to test our theories, so observation becomes vitally important. One of the first documented uses of the scientific method in an astronomical context was performed by Aristotle nearly 25 centuries ago. He noticed that during a lunar 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

6 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.

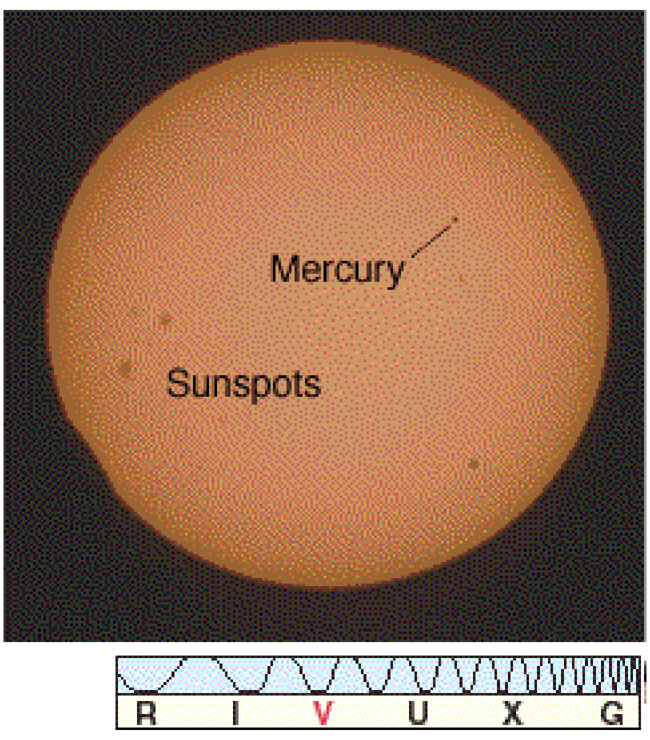


Figure 2.15 *A solar transit of Mercury. Such transits happen only about once per decade, because Mercury's orbit does not quite coincide with the plane of the ecliptic. Transits of Venus are even rarer, occurring only about twice per century.*

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.

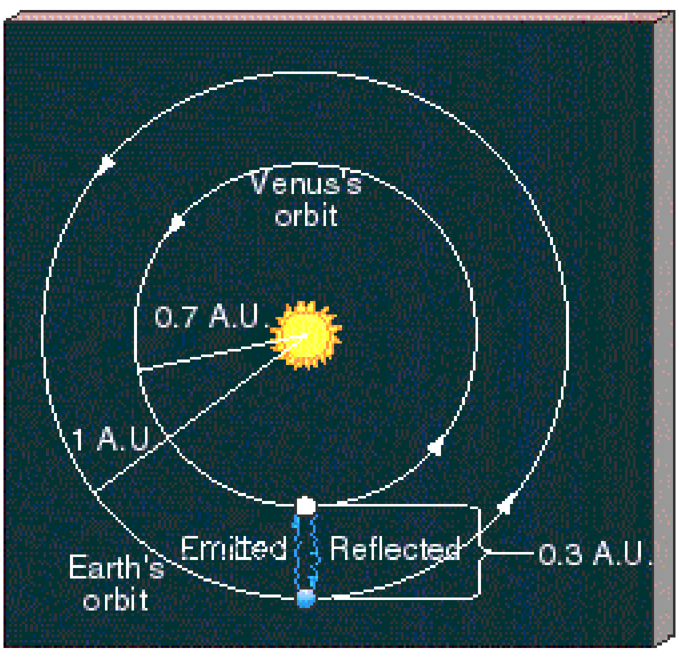


Figure 2.16 *Simplified geometry of the orbits of Earth and Venus as they move around the Sun. The wavy lines represent the paths along which radar signals might be transmitted toward Venus and received back at Earth at the moment when Venus is at its minimum distance from Earth. Because the radius of 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.

PREVIOUS NEXT CHAPTER REVIEW