early cultures—that Earth is a flat, motionless surface under a domelike sky across which the heavenly bodies move.

The story of how we progressed from this simple, intuitive view of Earth and the heavens to our modern understanding of Earth as a tiny planet in a vast cosmos is in many ways the story of the development of science itself. Our ancestors were curious about many aspects of the world around them, but astronomy held special interest. The Sun clearly plays a central role in our lives, governing daylight and darkness and marking the progression of the seasons. The Moon's connection to the tides would have been obvious to people living near the sea. The evident power of these celestial bodies probably explains why they attained prominent roles in many early religions and may be one reason why it seemed so important to know the sky. Careful observations of the sky also served practical needs by enabling ancient peoples to keep track of the time and the seasons—crucial requirements for agricultural societies.

FIGURE 2.1

This photograph, taken at Arches National Park with a 6-hour exposure, shows daily paths of stars in the sky. Notice that stars near the North Star (Polaris) make complete daily circles, while those farther from the North Star rise in the east and set in the west. Ancient people were quite familiar with patterns of motion like these.

As civilizations rose, astronomical observations became more careful and elaborate. In some cases, the results were recorded in writing. The ancient Chinese kept detailed records of astronomical observations beginning some 5000 years ago. By about 2500 years ago, written records allowed the Babylonians (in the region of modern-day Iraq) to predict eclipses with great success. Halfway around the world (and a few centuries later), the Mayans of Central America independently developed the same ability.

These ancient, recorded observations of astronomy represent databases of facts—the raw material of science. But in most cases for which we have historical records, it appears that these facts were never used for much beyond meeting immediate religious and practical needs. An exception was ancient Greece, where scholars attempted to use them to understand the architecture of the cosmos.

EARLY GREEK SCIENCE Greece gradually rose as a power in the Middle East beginning around 800 B.C. and was well established by about 500 B.C. Its geographical location placed it at a crossroads for travelers, merchants, and armies of northern Africa, Asia, and Europe. Building on the diverse ideas brought forth by the meeting of these many cultures, ancient Greek philosophers began to move human understanding of nature from the mythological to the rational.

We generally trace the origin of Greek science to the philosopher Thales (c. 624–546 B.C.; pronounced "THAY-lees"). Among his many accomplishments, Thales was the first person known to have addressed the question "What is the universe made of?" without resorting to supernatural explanations. His own guess—that the universe fundamentally consisted of water and that Earth was a flat disk on an infinite ocean—was not widely accepted even in his own time, but his mere asking of the question helped set the stage for all later science. For the first time, someone had suggested that the world was inherently understandable and not just the result of arbitrary or incomprehensible events.

The scholarly tradition begun by Thales was carried on by others, perhaps most famously by Plato (428–348 B.C.) and his student Aristotle (384–322 B.C.). Each Greek philosopher introduced new ideas, sometimes in contradiction to the ideas of others. None of these ideas rose quite to the level of modern science, primarily because the Greeks tended to rely more on pure thought and intuition than on observations or experimental tests. Nevertheless, with hindsight we can see at least three major innovations in Greek thought that helped pave the way for modern science.

First, the Greek philosophers developed a tradition of trying to understand nature without resorting to supernatural explanations. For example, although earlier Greeks might simply have accepted that the Sun moves across the sky because it is pulled by the god Apollo in his chariot—an idea whose roots were already lost in antiquity—the philosophers sought a natural explanation that caused them to speculate anew about the construction of the heavens. They were free to think creatively because they were not simply trying to prove preconceived ideas, and they recognized that new ideas should be open to challenge. As a result, they often worked communally, debating and testing each other's proposals. This tradition of challenging virtually every new idea remains one of the distinguishing features of scientific work today.

Second, the Greeks developed mathematics in the form of geometry. They valued this discipline for its own sake, and they understood its power, using geometry to solve both engineering and scientific problems. Without their mathematical sophistication, they would not have gone far in their attempts to make sense of the cosmos. Like the Greek tradition of challenging ideas, the use of mathematics to help explore the implications of new ideas remains an important part of modern science.

Third, while much of their philosophical activity consisted of subtle debates with little connection to observations or experiments, the Greeks also understood that an explanation about the world could not be right if it disagreed with observed facts. This willingness to discard explanations that simply don't work is also a crucial part of modern science.

THE GEOCENTRIC MODEL Perhaps the greatest Greek contribution to science came from the way they synthesized all three innovations into the idea of creating **models** of nature, an idea that is still central to modern science. Scientific models differ somewhat from the models you may be familiar with in everyday life. In our daily lives, we tend to think of models as miniature physical representations, such as model cars or airplanes. In contrast, a scientific model is a conceptual representation whose purpose is to explain and predict observed phenomena. For example, a model of Earth's climate uses logic, mathematics, and known physical laws in an attempt to represent the way in which the climate works. Its purpose is to explain and predict climate changes, such as the changes that may occur with global warming. Just as a model airplane does not faithfully represent every aspect of a real airplane, a scientific model may not fully explain all our observations of nature. Nevertheless, even the failings of a scientific model can be useful, because they often point the way toward building a better model.

Think About It Conceptual models aren't just important in science; they often affect day-to-day policy decisions. For example, economists use models to predict how new policies will affect the federal budget. Describe at least two other cases in which models affect our daily lives.

In astronomy, the Greeks constructed conceptual models of the universe in an attempt to explain what they observed in the sky, an effort that quickly led them past simplistic ideas of a flat Earth under a dome-shaped sky to a far more sophisticated view of the cosmos. One of the first crucial steps was taken by a student of Thales, Anaximander (c. 610–547 B.C.). In an attempt to explain the way the northern sky appears to turn around the North Star each day (see Figure 2.1), Anaximander suggested that the heavens must form a complete sphere—the **celestial sphere**—around Earth (Figure 2.2). Moreover, based on how the sky varies with latitude, he realized that Earth's surface must be curved, though he incorrectly guessed Earth to be a cylinder rather than a sphere.

The idea of a round Earth probably followed soon, and by about 500 B.C. it was part of the teachings of Pythagoras (c. 560–480 B.C.). He and his followers most likely adopted a spherical Earth for philosophical reasons: The Pythagoreans had a mystical interest in mathematical perfection, and they considered a sphere to be geometrically perfect. More than a century later, Aristotle cited observations of Earth's curved shadow on the Moon during lunar eclipses as evidence for a spherical Earth. Greek philosophers adopted a **geocentric** (Earth-centered) **model** of the universe, with a spherical Earth at the center of a great celestial sphere.

Incidentally, this shows the error of the widespread myth that Columbus proved Earth to be round when he sailed to America in 1492. Not only were scholars of the time well aware of Earth's round shape; they even knew Earth's approximate size: Earth's circumference was first measured (fairly accurately) in about 240 B.C. by the Greek scientist Eratosthenes. In fact, a likely reason why Columbus had so much difficulty finding a sponsor for his voyages was that he tried to argue a point on which he was dead wrong: He claimed the distance by sea from western Europe to eastern Asia to be much less than many scholars had estimated it to be. His erroneous belief would almost certainly have led his voyage to disaster if the Americas hadn't stood in his way.

THE MYSTERY OF PLANETARY MOTION If you watch the sky closely, you'll notice that while the patterns of the constellations seem not to change, the Sun, the Moon, and the five planets visible to the naked eye (Mercury, Venus, Mars, Jupiter, and Saturn) gradually move among the constellations from one day to the next. Indeed, the word *planet* comes from the Greek for "wanderer," and it originally referred to the Sun and Moon as well as to the five visible planets. Our seven-day week is directly traceable to the fact that seven "planets" are visible in the heavens (Table 2.1).

The wanderings of these objects convinced the Greek philosophers that there had to be more to the heavens than just a single sphere surrounding Earth. The Sun and Moon each move steadily through the constellations, with the Sun completing a circuit around the celestial sphere each year and the Moon completing each circuit in about a month (think

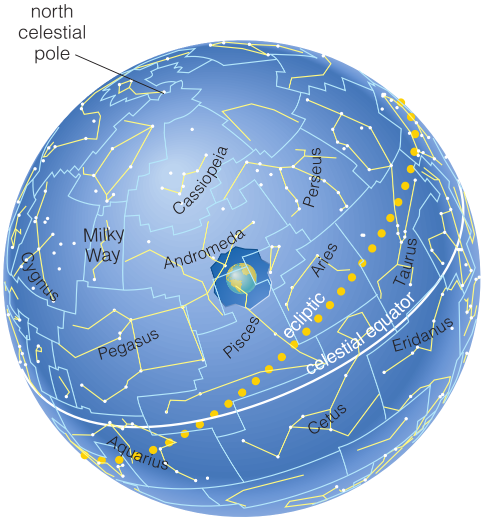


FIGURE 2.2
The early Greek geocentric model consisted of a central Earth surrounded by the celestial sphere, which is shown here marked with modern constellation borders and a few reference points and circles. We still use the idea of the celestial sphere when making astronomical observations, but we no longer imagine that it reflects reality.

TABLE 2.1 The Seven Days of the Week and the Astronomical Objects They Honor

The seven days were originally based on the seven visible "wanderers" of the sky. In English, the correspondence is still obvious for Sunday, "Moonday," and "Saturnday" (other days take names from Germanic gods); other connections are clearer in languages such as French and Spanish.

Object	*English*	*French*	*Spanish*
Sun	Sunday	dimanche	domingo
Moon	Monday	lundi	lunes
Mars	Tuesday	mardi	martes
Mercury	Wednesday	mercredi	miércoles
Jupiter	Thursday	jeudi	jueves
Venus	Friday	vendredi	viernes
Saturn	Saturday	samedi	sábado

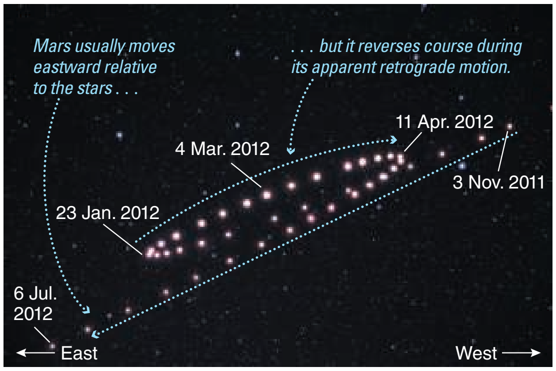


FIGURE 2.3
This composite of individual photos (taken at 5- to 7-day intervals in 2011 and 2012) shows a retrograde loop of Mars. Note that Mars is biggest and brightest in the middle of the retrograde loop, because that is where it is closest to Earth in its orbit.

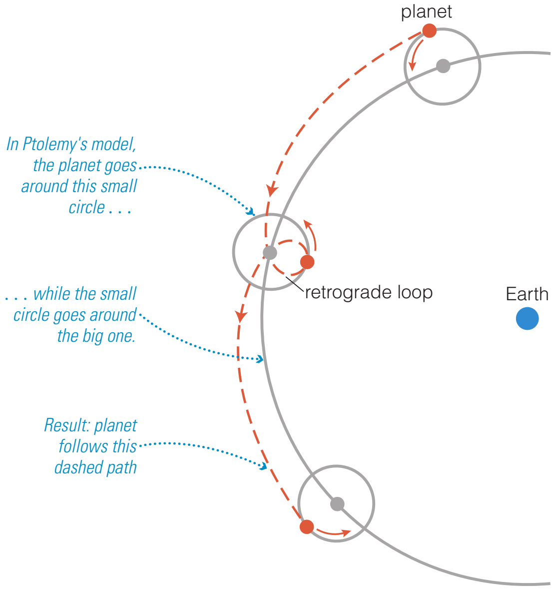


FIGURE 2.4 INTERACTIVE FIGURE
This diagram shows how the Ptolemaic model accounted for apparent retrograde motion. Each planet is assumed to move around a small circle that turns on a larger circle. The resulting path (dashed) includes a loop in which the planet goes backward as seen from Earth.

"moonth"). The Greeks could account for this motion by adding separate spheres for the Sun and Moon, each nested within the sphere of the stars, and allowing these spheres to turn at different rates from the sphere of the stars. But the five visible planets posed a much greater mystery.

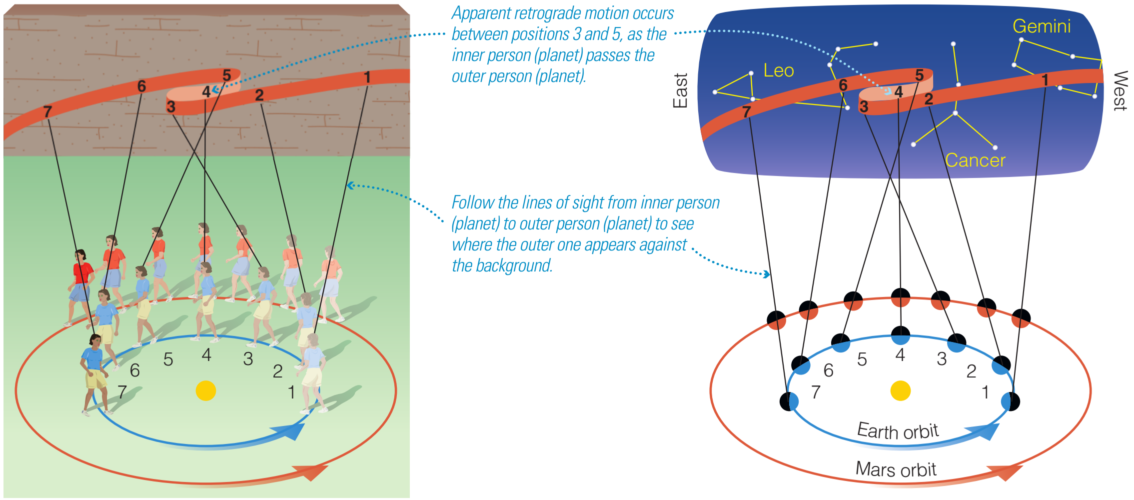
If you observe the position of a planet (such as Mars or Jupiter) relative to the stars over a period of many months, you'll find not only that its speed and brightness vary considerably but also that its direction of motion sometimes changes. While the planets usually move eastward relative to the constellations, sometimes they reverse course and go backward (Figure 2.3). These periods of **apparent retrograde motion** (*retrograde* means "backward") last from a few weeks to a few months, depending on the planet.

This seemingly erratic planetary motion was not so easy to explain with rotating spheres, especially because the Greeks generally accepted a notion of "heavenly perfection," enunciated most clearly by Plato, which demanded that all heavenly objects move in perfect circles. How could a planet sometimes go backward when moving in a perfect circle? The Greeks came up with a number of ingenious ideas that preserved Earth's central position, culminating with a complex model of planetary motion described by the astronomer Ptolemy (c. A.D. 100–170; pronounced "TOL-e-mee"); we refer to Ptolemy's model as the **Ptolemaic model** to distinguish it from earlier geocentric models. This model reproduced retrograde motion by having planets move around Earth on small circles that turned around larger circles. A planet following this circle-on-circle motion traces a loop as seen from Earth, with the backward portion of the loop mimicking apparent retrograde motion (Figure 2.4).

The circle-on-circle motion may itself seem somewhat complex, but Ptolemy found that he also had to use many other mathematical tricks, including putting some of the circles off-center, to get his model to agree with observations. Despite all this complexity, he achieved remarkable success: His model could correctly forecast future planetary positions to within a few degrees of arc—roughly equivalent to holding your hand at arm's length against the sky. Indeed, the Ptolemaic model generally worked so well that it remained in use for the next 1500 years. When Arabic scholars translated Ptolemy's book describing the model in around A.D. 800, they gave it the title *Almagest,* derived from words meaning "the greatest work."

AN ALTERNATIVE MODEL In about 260 B.C., the Greek scientist Aristarchus (c. 310–230 B.C.) offered a radical departure from the conventional wisdom: He suggested that Earth goes around the Sun, rather than vice versa. Little of Aristarchus's work survives to the present day, so we do not know exactly how he came up with his Sun-centered idea. We do know that he made measurements that convinced him that the Sun is much larger than Earth, so perhaps he simply concluded that it was more natural for the smaller Earth to orbit the larger Sun. In addition, he almost certainly recognized that a Sun-centered system offers a much more natural explanation for apparent retrograde motion.

You can see how the Sun-centered system explains retrograde motion with a simple demonstration (Figure 2.5a). Find an empty area (such as a sports field or a big lawn), and mark a spot in the middle to represent the Sun. You can represent Earth, walking counterclockwise around the Sun, while a friend represents a more distant planet (such as Mars, Jupiter, or Saturn) by walking counterclockwise around the Sun



Apparent retrograde motion occurs between positions 3 and 5, as the inner person (planet) passes the outer person (planet).

Follow the lines of sight from inner person (planet) to outer person (planet) to see where the outer one appears against the background.

a The retrograde motion demonstration: Watch how your friend (in red) usually appears to move forward against the background of the building in the distance but appears to move backward as you (in blue) catch up to and pass her in your "orbit."

b This diagram shows the same idea applied to a planet. Follow the lines of sight from Earth to Mars in numerical order. Notice that Mars appears to move westward relative to the distant stars (from points 3 to 5) as Earth passes it by in its orbit.

FIGURE 2.5 **INTERACTIVE FIGURE**
Apparent retrograde motion—the occasional "backward" motion of the planets relative to the stars—has a simple explanation in a Sun-centered solar system.

at a greater distance. Your friend should walk more slowly than you, because more distant planets orbit the Sun more slowly. As you walk, watch how your friend appears to move relative to buildings or trees in the distance. Although both of you always walk in the same direction around the Sun, your friend will appear to move backward against the background during the part of your "orbit" at which you catch up to and pass him or her. To understand the apparent retrograde motions of Mercury and Venus, which are closer to the Sun than is Earth, simply switch places with your friend and repeat the demonstration. The demonstration applies to all the planets. For example, because Mars takes about 2 years to orbit the Sun (actually, 1.88 years), it covers about half its orbit during the 1 year in which Earth makes a complete orbit. If you trace lines of sight from Earth to Mars from different points in their orbits, you will see that the line of sight usually moves eastward relative to the stars but moves westward during the time when Earth is passing Mars in its orbit (Figure 2.5b). Like your friend in the demonstration, Mars never actually changes direction. It only appears to change direction from our perspective on Earth.

Despite the elegance of this Sun-centered model for the universe, Aristarchus had little success in convincing his contemporaries to accept it. Some of the reasons for this rejection were purely philosophical and not based on any hard evidence. However, at least one major objection was firmly rooted in observations: Aristarchus's idea seemed inconsistent with observations of stellar positions in the sky.

To understand the inconsistency, imagine what would happen if you placed the Sun rather than Earth at the center of the celestial sphere, with Earth orbiting the Sun some distance away. In that case, Earth would be closer to different portions of the celestial sphere at different times of year. When we were closer to a particular part of the sphere, the stars on that part of the sphere would appear more widely separated than

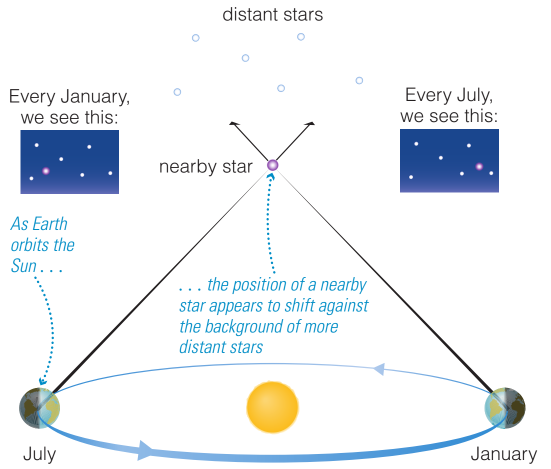


FIGURE 2.6 INTERACTIVE FIGURE
If Earth orbits the Sun, then over the course of each year we should see nearby stars shift slightly back and forth relative to more distant stars (*stellar parallax*). The Greeks could not detect any such shift, and used this fact to argue that Earth must be at the center of the universe. Today, we *can* detect stellar parallax with telescopic observations, proving that Earth does orbit the Sun. (This figure is greatly exaggerated; the actual shift is far too small to detect with the naked eye.)

they would when we were farther from that part of the sphere, just as the spacing between the two headlights on a car looks greater when you are closer to the car. This would create annual shifts in the separations of stars—but the Greeks observed no such shifts. They knew that there were only two possible ways to account for the lack of an observed shift: Either Earth was at the center of the universe or the stars were so far away as to make the shift undetectable by eye. To most Greeks, it seemed unreasonable to imagine that the stars could be *that* far away, which led them to conclude that Earth must hold a central place.

This argument about stellar shifts still holds when we allow for the reality that stars lie at different distances rather than all on the same sphere: As Earth orbits the Sun, we look at particular stars from slightly different positions at different times of year, causing the positions of nearby stars to shift slightly relative to more distant stars (Figure 2.6). Although such shifts are much too small to measure with the naked eye—because stars really are very far away [Section 3.2]—they are easily detectable with modern telescopes. These annual shifts in stellar position, called **stellar parallax,** now provide concrete proof that Earth really does go around the Sun.

THE ROOTS OF MODERN SCIENCE Although the Greeks ultimately rejected the correct idea—that Earth orbits the Sun—we have seen that they did so for reasons that made good sense at the time. Not all of their reasons would pass the test of modern science; for example, their preference for motion in perfect circles came only from their cultural ideas of aesthetics and not from any actual data. But they also went to a lot of effort to ensure that their models were consistent with observations, and in that way they laid the foundation of modern science. And while Aristarchus may not have won the day in his own time, his idea remained alive in books. Some 1800 years after he first proposed it, Aristarchus's Sun-centered model apparently came to the attention of a Polish astronomer named Nicholas Copernicus (1473–1543), who took the idea and ran with it in a way that led directly to the development of modern science. We'll return to this story shortly.

Why did the Greeks argue about the possibility of life beyond Earth?

Almost from the moment that Thales asked his question of what the universe was made of, the Greeks realized that the answer would have bearing on the possibility of life elsewhere. This might seem surprising in light of their geocentric beliefs, because they didn't think of the planets or stars as worlds in the way we think of them today. Instead, the Greeks generally considered the "world" to include both Earth and the heavenly spheres that they imagined to surround it, and they were at least open to the possibility that other such "worlds" might exist.

As we noted earlier, Thales guessed that the world consisted fundamentally of water, with Earth floating on an infinite ocean, but his student Anaximander imagined a more mystical element that he called *apeiron,* meaning "infinite." Anaximander suggested that all material things arose from and returned to the apeiron, which allowed him to imagine that worlds might be born and die repeatedly through eternal time. So even though he made no known claim of life existing elsewhere in the present, Anaximander essentially suggested that other Earths and other beings might exist at other times.

Other Greeks took the debate in a slightly different direction, and eventually a consensus emerged in favor of the world's having been built from four elements: fire, water, earth, and air. However, two distinct schools of thought emerged concerning the nature and extent of these elements:

- The *atomists* held that both Earth and the heavens were made from an infinite number of indivisible atoms of each of the four elements.
- The *Aristotelians* (after Aristotle) held that the four elements—not necessarily made from atoms—were confined to the realm of Earth, while the heavens were made of a fifth element, often called the *aether* (or *ether*) or the *quintessence* (literally, "the fifth essence").

The differences in the two schools of thought led to two fundamentally different conclusions about the possibility of extraterrestrial life.

Think About It Look up the words *ethereal* and *quintessence* in the dictionary. How do their definitions relate to the Aristotelian idea that the heavens were composed of an element distinct from the elements of Earth? Explain.

The atomist doctrine was developed largely by Democritus (c. 470–380 B.C.), and his views show how the idea led almost inevitably to belief in extraterrestrial life. Democritus argued that the world—both Earth and the heavens—had been created by the random motions of infinite atoms. Because this idea held that the number of atoms was infinite, it was natural to assume that the same processes that created our world could also have created others. This philosophy on life beyond Earth is clearly described in the following quotation from a later atomist, Epicurus (341–270 B.C.):

> *There are infinite worlds both like and unlike this world of ours … we must believe that in all worlds there are living creatures and plants and other things we see in this world.**

Aristotle had a different view. He believed that each of the four elements had its own natural motion and place. For example, he believed that the element earth moved naturally toward the center of the universe, an idea that offered an explanation for the Greek assumption that Earth resided in a central place. The element fire, he claimed, naturally rose away from the center, which explained why flames jut upward into the sky. These incorrect ideas about physics, which were not disproved until the time of Galileo and Newton almost 2000 years later, caused Aristotle to reject the atomist idea of many worlds. If there was more than one world, there would be more than one natural place for the elements to go, which would be a logical contradiction. Aristotle concluded:

> *The world must be unique…. There cannot be several worlds.*

Interestingly, Aristotle's philosophies were not particularly influential until many centuries after his death. His books were preserved and valued—in particular, by Islamic scholars of the late first millennium—but they were unknown in Europe until they were translated into Latin in the twelfth and thirteenth centuries. St. Thomas Aquinas (1225–1274)

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*From Epicurus's "Letter to Herodotus"; the authors thank David Darling for finding this quotation and the one from Aristotle, both of which appear in Darling's book *The Extraterrestrial Encyclopedia*, Three Rivers Press, 2000.

integrated Aristotle's philosophy into Christian theology. At this point, the contradiction between the Aristotelian notion of a single world and the atomist notion of many worlds became a subject of great concern to Christian theologians. Moreover, because the atomist view held that our world came into existence through random motions of atoms, and hence without the need for any intelligent Creator, atomism became associated with atheism. The debate about extraterrestrial life thereby became intertwined with debates about religion. Even today, the theological issues are not fully settled, and echoes of the ancient Greek debate between the atomists and the Aristotelians still reverberate in our time.

2.2 The Copernican Revolution

Greek ideas gained great influence in the ancient world, in large part because the Greeks proved to be as adept at politics and war as they were at philosophy. In about 330 B.C., Alexander the Great began a series of conquests that expanded the Greek Empire throughout the Middle East. Alexander had a keen interest in science and education, perhaps because he grew up with Aristotle as his personal tutor. Alexander established the city of Alexandria in Egypt, and his successors founded the renowned Library of Alexandria. Though it is sometimes difficult to distinguish fact from legend in stories of this great Library, there is little doubt that it was once the world's preeminent center of research, housing up to a half million books written on papyrus scrolls. While the details of the Library's destruction are hazy and subject to disagreement among historians, the Library was ultimately destroyed, and most of its books were lost forever.

The relatively few books from the Library that survive today were preserved primarily thanks to the rise of a new center of intellectual inquiry in Baghdad (in present-day Iraq). As European civilization fell into the Dark Ages, scholars of the new religion of Islam sought knowledge of mathematics and astronomy in hopes of better understanding the wisdom of Allah. The Islamic scholars translated and thereby saved many of the remaining ancient Greek works. Building on what they learned from the Greek manuscripts, they went on to develop the mathematics of algebra as well as many new instruments and techniques for astronomical observation.

The Islamic world of the Middle Ages was in frequent contact with Hindu scholars from India, who in turn brought ideas and discoveries from China. Hence, the intellectual center in Baghdad achieved a synthesis of the surviving work of the ancient Greeks, the Indians, the Chinese, and the contributions of its own scholars. This accumulated knowledge spread throughout the Byzantine Empire (the eastern part of the former Roman Empire). When the Byzantine capital of Constantinople (modern-day Istanbul) fell in 1453, many Eastern scholars headed west to Europe, carrying with them the knowledge that helped ignite the European Renaissance. The stage was set for a dramatic rethinking of humanity and our place in the universe.

How did the Copernican revolution further the development of science?

In 1543, Nicholas Copernicus published *De Revolutionibus Orbium Coelestium* ("Concerning the Revolutions of the Heavenly Spheres"), launching what we now call the **Copernican revolution.** In his book, Copernicus revived Aristarchus's radical suggestion of a Sun-centered solar system and described the idea with enough mathematical detail to make it a valid competitor to the Earth-centered, Ptolemaic model. Over the next century and a half, philosophers and scientists (who were often one and the same) debated and tested the Copernican idea. Many of the ideas that now form the foundation of modern science first arose as this debate played out. Indeed, the Copernican revolution had such a profound impact on philosophy that we cannot understand modern science without first understanding the key features of this revolution.

COPERNICUS—THE REVOLUTION BEGINS By the time of Copernicus's birth in 1473, tables of planetary motion based on the Ptolemaic model had become noticeably inaccurate. However, few people were willing to undertake the difficult calculations required to revise the tables. Indeed, the best tables available were already two centuries old, having been compiled under the guidance of the Spanish monarch Alphonso X (1221–1284). Commenting on the tedious nature of the work involved, the monarch is said to have complained that "If I had been present at the creation, I would have recommended a simpler design for the universe."

Copernicus began studying astronomy in his late teens. He soon became aware of the inaccuracies of the Ptolemaic predictions and began a quest for a better way to predict planetary positions. He adopted Aristarchus's Sun-centered idea, probably because he was drawn to its simple explanation for the apparent retrograde motion of the planets (see Figure 2.5). As he worked out the mathematical details of his model, Copernicus discovered simple geometric relationships that allowed him to calculate each planet's orbital period around the Sun and its relative distance from the Sun in terms of Earth–Sun distance. The success of his model in providing a geometric layout for the solar system further convinced him that the Sun-centered idea must be correct. Despite his own confidence in the model, Copernicus was hesitant to publish his work, fearing that the idea of a moving Earth would be considered absurd.* However, he discussed his system with other scholars, including high-ranking officials of the Church, who urged him to publish a book. Copernicus saw the first printed copy of his book on the day he died—May 24, 1543.

Publication of the book spread the Sun-centered idea widely, and many scholars were drawn to its aesthetic advantages. However, the Copernican model gained relatively few converts over the next 50 years, for a good reason: It didn't work all that well. The primary problem was that while Copernicus had been willing to overturn Earth's central place in the cosmos, he held fast to the ancient belief that heavenly motion must occur in perfect circles. This incorrect assumption forced him to add numerous complexities to his system (including circles on circles much like those used by Ptolemy) to get it to make decent predictions. In the end, his complete model was no more accurate and no less complex than the Ptolemaic model, and few people were willing to throw out thousands of years of tradition for a new model that worked just as poorly as the old one.

TYCHO—A NEW STANDARD IN OBSERVATIONAL DATA Part of the difficulty faced by astronomers who sought to improve either the Ptolemaic or the

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*Indeed, in the Preface of *De Revolutionibus*, Copernicus offered a theological defense of the Sun-centered idea: "Behold, in the middle of the universe resides the Sun. For who, in this most beautiful Temple, would set this lamp in another or a better place, whence to illumine all things at once?"

FIGURE 2.7
Tycho Brahe in his naked-eye observatory, which worked much like a giant protractor. He could sit and observe a planet through the rectangular hole in the wall as an assistant used a sliding marker to measure the angle on the protractor.

Copernican model was a lack of quality data. The telescope had not yet been invented, and existing naked-eye observations were not particularly accurate. In the late sixteenth century, Danish nobleman Tycho Brahe (1546–1601), usually known simply as Tycho (commonly pronounced "TIE-koe"), set about correcting this problem.

Tycho was an eccentric genius who, at age 20, lost part of his nose in a sword fight with another student over who was the better mathematician. Taking advantage of his royal connections, he built large naked-eye observatories (Figure 2.7) that worked much like giant protractors, and over a period of three decades he used them to measure planetary positions to within 1 minute of arc ($\frac{1}{60}$ of 1°)—which is less than the thickness of a fingernail held at arm's length.

KEPLER—A SUCCESSFUL MODEL OF PLANETARY MOTION Tycho never came up with a fully satisfactory explanation for his observations (though he made a valiant attempt), but he found someone else who did. In 1600, he hired a young German astronomer named Johannes Kepler (1571–1630). Kepler and Tycho had a strained relationship,* but in 1601, as he lay on his deathbed, Tycho begged Kepler to find a system that would make sense of his observations so "that it may not appear I have lived in vain."

Kepler was deeply religious and believed that understanding the geometry of the heavens would bring him closer to God. Like Copernicus, he believed that planetary orbits should be perfect circles, so he worked diligently to match circular motions to Tycho's data. After years of effort, he found a set of circular orbits that matched most of Tycho's observations quite well. Even in the worst cases, which were for the planet Mars, Kepler's predicted positions differed from Tycho's observations by only about 8 arcminutes.

Kepler surely was tempted to ignore these discrepancies and attribute them to errors by Tycho. After all, 8 arcminutes is barely one-fourth the angular diameter of the full moon. But Kepler trusted Tycho's careful work. The small discrepancies finally led Kepler to abandon the idea of circular orbits—and to find the correct solution to the ancient riddle of planetary motion. About this event, Kepler wrote,

> *If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.*

Kepler's decision to trust the data over his preconceived beliefs marked an important transition point in the history of science. Once he abandoned perfect circles, he was free to try other ideas and he soon hit on the correct one: Planetary orbits take the shapes of the special types of ovals known as *ellipses.* He then used his knowledge of mathematics to put his new model of planetary motion on a firm footing, expressing the key features of the model with what we now call **Kepler's laws of planetary motion:**

- **Kepler's first law:** *The orbit of each planet about the Sun is an ellipse with the Sun at one focus* (Figure 2.8). This law tells us that a planet's distance from the Sun varies during its orbit. Its closest point is called **perihelion** (from the Greek for "near the Sun") and its farthest point is called **aphelion** ("away from the Sun"). The *average*

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*For a particularly moving version of the story of Tycho and Kepler, see *Cosmos*, by Carl Sagan, Episode 3.

of a planet's perihelion and aphelion distances is the length of its **semimajor axis** (which we will refer to simply as the planet's average distance from the Sun).

- **Kepler's second law:** *A planet moves faster in the part of its orbit nearer the Sun and slower when farther from the Sun, sweeping out equal areas in equal times.* As shown in Figure 2.9, the "sweeping" refers to an imaginary line connecting the planet to the Sun, and keeping the areas equal means that the planet moves a greater distance (and hence is moving faster) when it is near perihelion than it does in the same amount of time near aphelion.
- **Kepler's third law:** *More distant planets orbit the Sun at slower average speeds, obeying the precise mathematical relationship* $p^2 = a^3$; p is the planet's orbital period in years and a is its average distance (semimajor axis) from the Sun in astronomical units. [One **astronomical unit** (**AU**) is defined as Earth's average distance from the Sun, or about 149.6 million kilometers.] The mathematical statement of Kepler's third law allows us to calculate the average orbital speed of each planet (Figure 2.10).

Kepler published his first two laws in 1609 and his third in 1619. Together, they made a model that could predict planetary positions with far greater accuracy than Ptolemy's Earth-centered model. Indeed, Kepler's model has worked so well that we now see it not just as an abstract model, but instead as revealing a deep, underlying truth about planetary motion.

GALILEO—ANSWERING THE REMAINING OBJECTIONS The success of Kepler's laws in matching Tycho's data provided strong evidence in favor of Copernicus's placement of the Sun, rather than Earth, at the center of the solar system. Nevertheless, many scientists still voiced reasonable objections to the Copernican view. There were three basic objections, all rooted in the 2000-year-old beliefs of Aristotle:

- First, Aristotle had held that Earth could not be moving because, if it were, objects such as birds, falling stones, and clouds would be left behind as Earth moved along its way.
- Second, the idea of noncircular orbits contradicted the view that the heavens—the realm of the Sun, Moon, planets, and stars—must be perfect and unchanging.
- Third, no one had detected the stellar parallax that should occur if Earth orbits the Sun.

Galileo Galilei (1564–1642), nearly always known by his first name, answered all three objections.

Galileo defused the first objection with experiments that almost single-handedly overturned the Aristotelian view of physics. In particular, he used experiments with rolling balls to demonstrate that a moving object remains in motion *unless* a force acts to stop it (an idea now codified in Newton's first law of motion). This insight explained why objects that share Earth's motion through space—such as birds, falling stones, and clouds—should *stay* with Earth rather than falling behind as Aristotle had argued. This same idea explains why passengers stay with a moving airplane even when they leave their seats.

The notion of heavenly perfection was already under challenge by Galileo's time, because Tycho had observed a supernova and proved

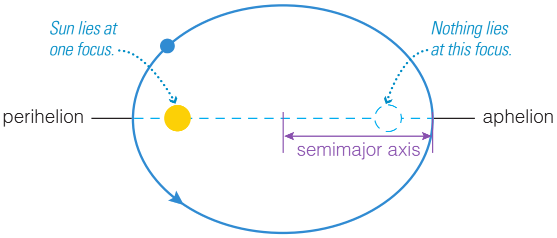
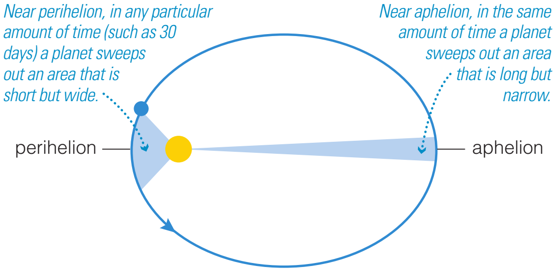


FIGURE 2.8 INTERACTIVE FIGURE

Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus. (The ellipse shown here is more eccentric, or "stretched out," than any of the actual planetary orbits in our solar system.)



The areas swept out in 30-day periods are all equal.

FIGURE 2.9 INTERACTIVE FIGURE

Kepler's second law: As a planet moves around its orbit, it moves faster when closer to the Sun than when farther away, so that an imaginary line connecting it to the Sun sweeps out equal areas (the shaded regions) in equal times.

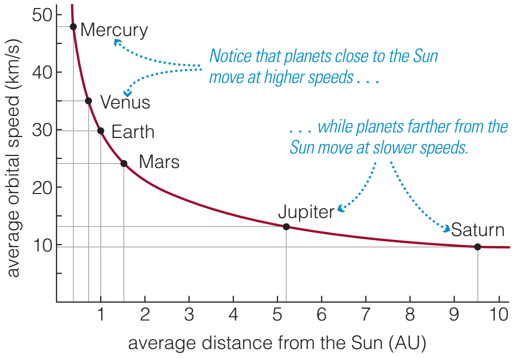


FIGURE 2.10

This graph, based on Kepler's third law ($p^2 = a^3$) and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

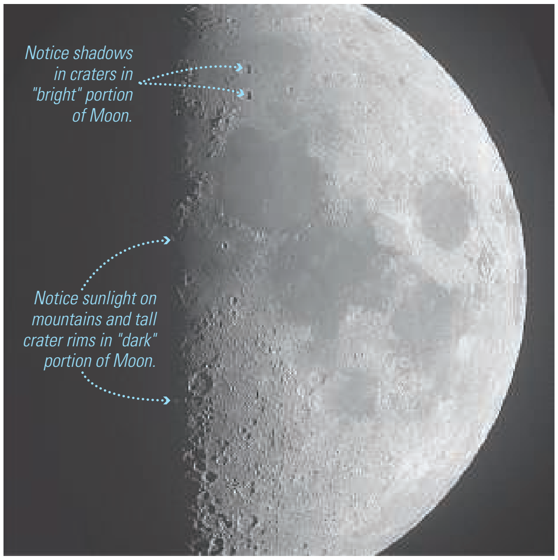


FIGURE 2.11
Shadows visible near the dividing line between the light and dark portions of the lunar face prove that the Moon's surface is not perfectly smooth.

that comets lie beyond the Moon; these observations showed that the heavens *do* sometimes undergo change. But Galileo drove the new idea home after he built a telescope in late 1609. (Galileo did not invent the telescope, but his innovations made it much more powerful.) Through his telescope, Galileo saw sunspots on the Sun, which were considered "imperfections" at the time. He also used his telescope to prove that the Moon has mountains and valleys like the "imperfect" Earth by noticing the shadows cast near the dividing line between the light and dark portions of the lunar face (Figure 2.11). If the heavens were not perfect, then the idea of elliptical orbits (as opposed to "perfect" circles) was not so objectionable.

The third objection—the absence of observable stellar parallax—had been a particular concern of Tycho's. Based on his estimates of the distances of stars, Tycho believed that his naked-eye observations were sufficiently precise to detect stellar parallax if Earth did in fact orbit the Sun. Refuting Tycho's argument required showing that the stars were more distant than Tycho had thought and therefore too distant for him to have observed stellar parallax. Although Galileo didn't actually prove this fact, he provided strong evidence in its favor. For example, he saw with his telescope that the Milky Way resolved into countless individual stars. This discovery helped him argue that the stars were far more numerous and more distant than Tycho had believed.

In hindsight, the final nails in the coffin of the Earth-centered universe came with two of Galileo's earliest discoveries through the telescope. First, he observed four moons clearly orbiting Jupiter, not Earth. Soon thereafter, he observed that Venus goes through phases in a way that proved that it must orbit the Sun and not Earth (Figure 2.12). Together, these observations offered clear proof that Earth is *not* the center of everything.*

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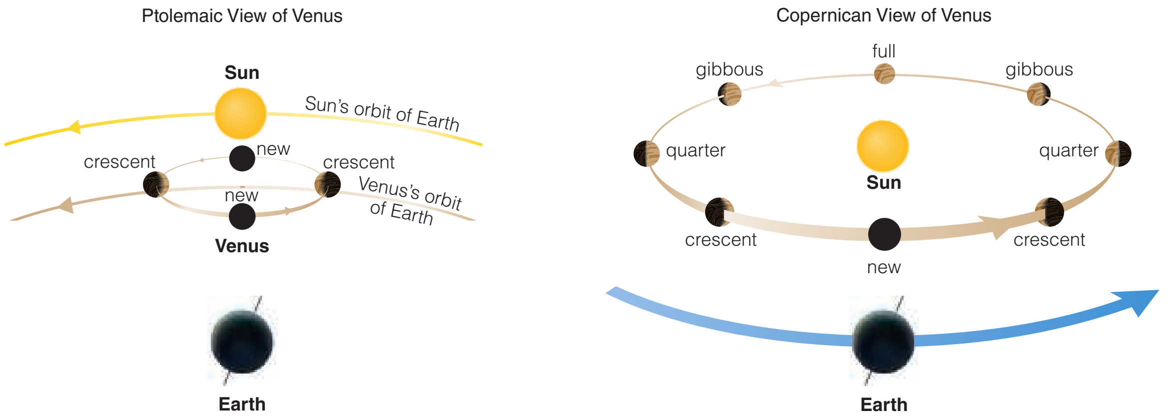
*While these observations proved that Earth is not the center of everything, they did not by themselves prove that Earth orbits the Sun; direct proof of that fact did not come until later, with measurements of stellar parallax and of an effect known as the *aberration of starlight* that also occurs only because of Earth's motion. Nevertheless, the existence of Jupiter's moons showed that moons can orbit a moving planet like Jupiter, which overcame some critics' complaints that the Moon could not stay with a moving Earth, and the proof that Venus orbits the Sun provided clear validation of Kepler's model of Sun-centered planetary motion.

FIGURE 2.12 **INTERACTIVE FIGURE**
Galileo's telescopic observations of Venus proved that it orbits the Sun rather than Earth.



a In the Ptolemaic system, Venus orbits Earth, moving around a small circle on its larger orbital circle; the center of the small circle lies on the Earth-Sun line. Thus, if this view were correct, Venus's phases would range only from new to crescent.

b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus really does orbit the Sun.

Although we now recognize that Galileo won the day, the story was more complex in his own time, when Catholic Church doctrine still held Earth to be the center of the universe. On June 22, 1633, Galileo was brought before a Church inquisition in Rome and ordered to recant his claim that Earth orbits the Sun. Nearly 70 years old and likely fearing for his life, Galileo did as ordered. However, legend has it that as he rose from his knees, he whispered under his breath, *Eppur si muove*—Italian for "And yet it moves." (Given the likely consequences if Church officials had heard him say this, most historians doubt the legend.)

The Church did not formally vindicate Galileo until 1992, but the Church had given up the argument long before that. Today, Catholic scientists are at the forefront of much astronomical research, and official Church teachings are compatible not only with Earth's planetary status but also with the theories of the Big Bang and the subsequent evolution of the cosmos and of life.

Think About It Although the Catholic Church today teaches that science and the Bible are compatible, not all religious denominations hold the same belief. Do *you* think that science and the Bible are compatible? Defend your opinion.

NEWTON—THE REVOLUTION CONCLUDES Kepler's model worked so well and Galileo so successfully defused the remaining objections that by about the 1630s, scientists were nearly unanimous in accepting the validity of Kepler's laws of planetary motion. However, no one yet knew *why* the planets should move in elliptical orbits with varying speeds. The question became a topic of great debate, and a few scientists even guessed the correct answer—but they could not prove it, largely because the necessary understanding of physics and mathematics didn't exist yet. This understanding finally came through the remarkable work of Sir Isaac Newton (1642–1727), who invented the mathematics of calculus and used it to explain and discover many fundamental principles of physics.

In 1687, Newton published a famous book usually called *Principia,* short for *Philosophiae Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"). In it, he laid out precise mathematical descriptions of how motion works in general, ideas that we now describe as **Newton's laws of motion.** For reference, Figure 2.13 illustrates the three laws of motion, although we will not make much use of them in this book. (Be careful not to confuse *Newton's* three laws, which apply to all motion, with *Kepler's* three laws, which describe only the motion of planets moving about the Sun.)

Newton continued on in *Principia* to describe his universal law of gravitation (see Section 2.4), and then used mathematics to prove that Kepler's laws are natural consequences of the laws of motion and gravity. In essence, Newton had created a new model for the inner workings of the universe in which motion is governed by clear laws and the force of gravity. The model explained so much about the nature of motion in the everyday world, as well as about the movements of the planets, that the geocentric idea could no longer be taken seriously.

LOOKING BACK AT REVOLUTIONARY SCIENCE Fewer than 150 years passed between Copernicus's publication of *De Revolutionibus* in 1543 and Newton's publication of *Principia* in 1687, such a short time in the scope of human history that we call it a revolution. A quick look back shows that

Cosmic Calculations 2.1

KEPLER'S THIRD LAW

When Kepler discovered his third law ($p^2 = a^3$), he knew only that it applied to the orbits of planets about the Sun. In fact, it applies to any orbiting object as long as the following two conditions are met:

1. The object orbits the Sun *or* another object of precisely the same mass.
2. We use units of *years* for the orbital period and *AU* for the orbital distance.

(Newton extended the law to *all* orbiting objects; see Cosmic Calculations 7.1.)

Example 1: The largest asteroid, Ceres, orbits the Sun at an average distance (semimajor axis) of 2.77 AU. What is its orbital period?

Solution: Both conditions are met, so we solve Kepler's third law for the orbital period p and substitute the given orbital distance, $a = 2.77$ AU:

$$p^2 = a^3 \Rightarrow p = \sqrt{a^3} = \sqrt{2.77^3} \approx 4.6$$

Ceres has an orbital period of 4.6 years.

Example 2: A planet is discovered orbiting every three months around a star of the same mass as our Sun. What is the planet's average orbital distance?

Solution: The first condition is met, and we can satisfy the second by converting the orbital period from months to years: $p = 3$ months $= 0.25$ year. We now solve Kepler's third law for the average distance a:

$$p^2 = a^3 \Rightarrow a = \sqrt[3]{p^2} = \sqrt[3]{0.25^2} \approx 0.40$$

The planet orbits its star at an average distance of 0.40 AU, which is nearly the same as Mercury's average distance from the Sun.