CHAPTER 2

Moving the Earth

2.1 ASTRONOMY, MOTION, AND MECHANICS

Galileo's discoveries about motion formed a major part of a much larger development across all of the sciences, a development now known as the *Scientific Revolution*. In the study of the physical world, the science of motion, or mechanics, joined with the science of astronomy to form the basic approach to modern physics. Paralleling the revolution in mechanics, the revolution in astronomy involved an extremely difficult transition for most people from the common-sense view of the Universe in which the Earth is stationary at the center of the Universe to our current, more abstract, view that the Earth is actually spinning on its axis as it orbits around a star, our Sun, as the third planet. Since the Earth was now seen as a moving object, the revolution in mechanics helped to encourage the revolution in astronomy, and vice versa. This chapter looks at the parallel developments in astronomy, before turning to the *causes* of motion in the next chapter.

Once again, Galileo played a key role in terms of both the new science and the new issues that it raised.

2.2 THE SCIENTIFIC REVOLUTION

Think back to what you may have learned in a social studies or history course about the period from A.D. 1550 to about 1700. This was the period of the Renaissance—the word for "rebirth" in French—that spread out from Italy across the Western world. The Renaissance movement brought new forms of art, music, and courageous new ideas about the Universe and humanity's place in it. Curiosity and a questioning attitude became acceptable, even prized.

The art of Botticelli, Rembrandt, and other great masters showed an enthusiasm for exploring the natural world that paralleled a similar enthusiasm in science and the actual explorations and discoveries of the seafaring explorers. New instruments, such as the telescope and the microscope,

FIGURE 2.1 Rembrandt's *The Three Trees* (1643).

opened up new worlds that had never been seen before. New devices, such as the barometer, thermometer, vacuum pump, and mechanical clock, enabled more sophisticated experimental research, and the invention of the printing press enabled the rapid dissemination of a researcher's works to an ever-growing audience. Among these works were also the newly discovered writings of such important Greek thinkers as Plato and Archimedes. Many of these were first encountered by Europeans in Arabic translation during and after the Crusades. In awe of what they found, European scholars eagerly translated and studied these ancient works, both as curiosities and as alternatives to Aristotle. Within a few generations there arose a new ideal of humankind, the confident individual full of curiosity and the joy of living.

Along with the new enthusiasm for learning about the natural world came a new freedom of thought encouraged by the Protestant Reformation and a new freedom from economic and social constraints encouraged by the rise of a new commercial middle class. The growth of cities as commercial centers in Europe and the breakdown of the hierarchical feudal order in society enabled the rise of a middle class that could afford to send its sons to the universities to learn about the heavens, instead of sending them to the fields to work from dawn to dusk. The growing numbers of these young men (there were only a few women in science at that time), their growing science, and their growing economic and cultural impact led to the founding of state-sponsored societies and academies of science. Here, amidst debate and critical peer review, the new scientists established the methods and the content of today's physics and many other contemporary sciences. From Europe the new sciences and the new scientific approach quickly spread throughout the entire world, constantly growing and progressing ever since through the contributions of many different cultures and peoples around the globe.

Let's look at one of the beginnings of the new physical sciences: astronomy.

2.3 COPERNICUS

Within the emerging Renaissance culture lived a Polish church official and mathematical astronomer named Nikolaj Koppernigk (1473–1543), better known as Nicolas Copernicus. Copernicus became famous for presenting the first viable, quantitative argument for the so-called *heliocentric theory* of the Sun and planets, which we accept today. In the heliocentric theory (from the Greek word "helios," for sun), the Earth is not the center of the

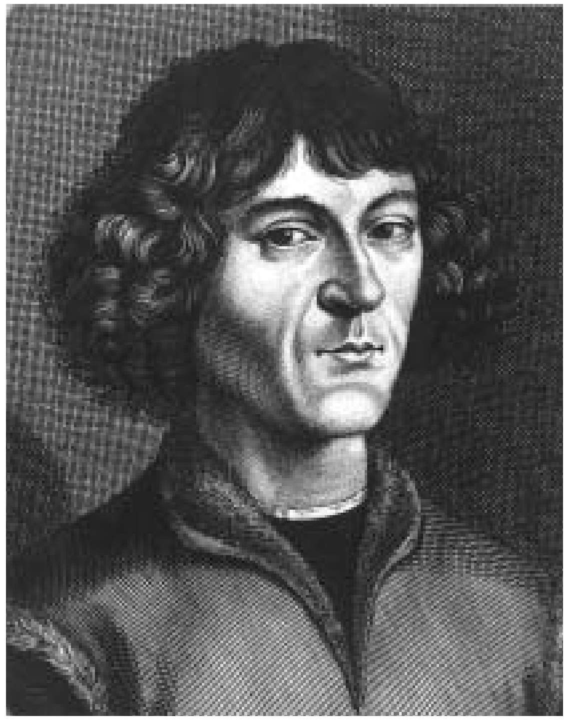


FIGURE 2.2 Nicolaus Copernicus (1473–1543).

Universe, but instead it and all the other planets orbit the Sun. The Earth orbits the Sun in one year, while at the same time the Earth rotates on its axis once a day. Copernicus's ideas were so revolutionary at the time that his work is often known as the Copernican Revolution.

Copernicus was a student in Poland when Columbus discovered America in 1492. An outstanding astronomer and mathematician, he was also a talented and respected churchman, jurist, diplomat, physician, and economist. During his further studies in Italy he had read the newly discovered writings of Plato and other early philosophers and astronomers. Plato provided a welcome alternative to Aristotle for those seeking new answers. What better way to challenge one old master (Aristotle) than with another (Plato)!

As a canon (priest) at the Cathedral of Frauenberg, Copernicus was busy with church and civic affairs, but he found time to work on astronomy and calendar reform. It is said that on the day of his death in 1543 he saw the first copy of the great book on which he had worked most of his life. It was this book, *On the Revolutions of the Heavenly Spheres*, that opened a whole new vision of the Universe.

FIGURE 2.3 Page from Copernicus's *On the Revolutions of the Heavenly Spheres.*

We will look briefly at the old vision of the Universe in order to see what was new about Copernicus's new vision.

2.4 THE GEOCENTRIC VIEW

Since we live on Earth and observe the motions of objects in the heavens from Earth, we naturally tend to think of ourselves as being at rest on Earth while everything else is moving around us and that we are at the center of the Universe. Since the heavenly objects appear to move around us on circular paths centered on Earth, we naturally tend to think of ourselves as being at the center of the Universe. This is called the *geocentric view* of the Universe, from the Greek word "geo" for "earth" (from which we also have the words "geology" and "geography"). If you have had an opportunity to study relative motion in the laboratory or to observe the motion of the Sun or Moon, you will know that it is not possible through direct observation to decide if it is we who are at rest and the stars and Sun that are moving,

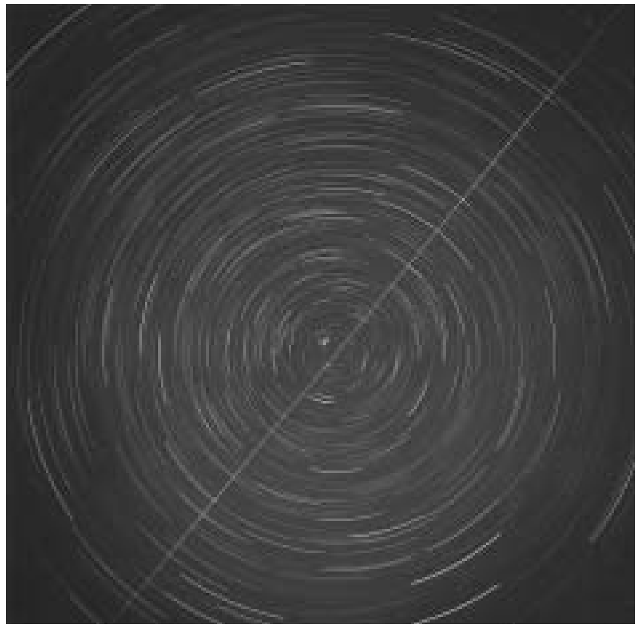


FIGURE 2.4 Time exposure showing stars' trail around the north celestial pole. The diagonal line represents the path of an artificial earth satellite.

or if it is we who are moving and the stars and Sun that are at rest. For instance, when the Sun "sets" on the horizon, is it the Sun that is moving down below the stationary horizon, or is it the horizon that is moving up to the stationary Sun as the Earth rotates?

No wonder Aristotle's very plausible and well-constructed theory of the Universe was so well received and widely accepted for so long (see the Prologue). But there was one problem with Aristotle's cosmology (theory of the Universe): it was not *quantitative*; it was only *qualitative*. It did not provide a precise, mathematical account of the observed positions and motions of the Sun and Moon and planets, and that is what astronomers really wanted—since astronomy at that time was a considered a branch of mathematics, and astronomers were employed in calculating celestial phenom-

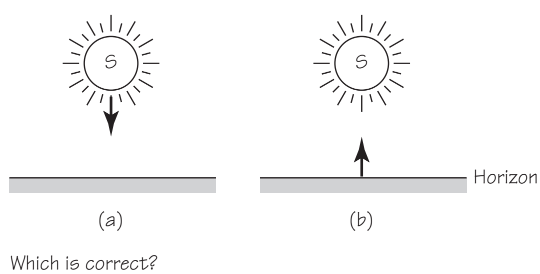


FIGURE 2.5 Sun vs. Earth: which is moving?

ena, reforming the calendar, and performing astrological calculations, which involved a mathematical study of the planets. (However, because it also assumes the influence of the planets on human affairs, an assumption that is not confirmed by the evidence, astrology is not considered a science.)

The Observations

What do you actually see when you look up at the sky?

You see a lot of different celestial objects. Every object in the sky can be located by angles. The two most common angles are the angle above the horizon, called the altitude, and the angle clockwise from due north, the azimuth.

Figure 2.6 depicts what the sky looks like to anyone even today who stands outside, at night for a while, away from lights and buildings: the sky is seemingly a large dome, centered on us. The part we see is part of a *celestial sphere*. If you wait long enough, or come back in an hour, the stars and Sun and Moon (when visible) appear to move slowly from east to west, where they then "set" (go over the horizon).

If you try looking at the positions of the Moon and Sun, each at the same time every day, you will notice something strange. From the Earth, they both seem to circle overhead more slowly than the stars. The Sun seems to fall about 1° behind where it was the day before at the exact same time, while the Moon falls about 12° behind. The next day they are again, respectively, another 1° and 12° behind; after a week the Sun is 7° behind, and so on. How long will it take for the Sun and Moon to slide all the way around a 360° circle and be in line again with the same stars? For the Sun it would take about 360 days, moving at about 1° per day (more precisely,

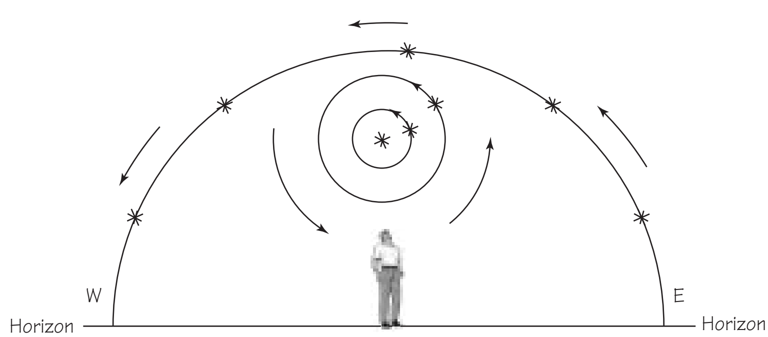


FIGURE 2.6 Seen from the Earth on a clear night, the stars appear to lie on a large dome that rotates slowly from east to west around a fixed star, Polaris.

it is 365.24220 days). In other words, it would take one full year for the Sun to be "lapped" by the stars; indeed, this is how we *define* our year. As seen from the Earth the Moon would take nearly 30 days (more precisely, 29.57333 days) for a complete lunar phase cycle, (or about 27.32152 days as seen from the stars)—about 1 month.

The slipping of the Sun and Moon around the 360° of the celestial sphere suggested to early observers that the dome of the sky is closed, and that it is in fact a sphere. Seen from the Earth, such as outside your building, this dome appears to circle around us once a day from east to west. To the ancients it seemed that the celestial objects *are* actually on the celestial sphere, which rotates around us once every 24 hr, with the Sun and Moon slipping behind in their own way.

The ancient picture of the Universe is presented in Figure 2.7. This shows a closed celestial sphere centered on a spherical Earth with north and south poles and an equator in line with the celestial poles and equator. You may be surprised to see that they thought of the Earth, not as a flat disk, but as a round sphere, just as we do today.

The Round Earth

Contrary to common opinion, it was not Columbus who discovered that the Earth is round when he landed in America in 1492. It was already known to the ancient Greeks, as well as in Columbus's day, that the Earth is round, although the common folk among the sailors on his ships may have believed otherwise. (What Columbus did not know, but which was also known

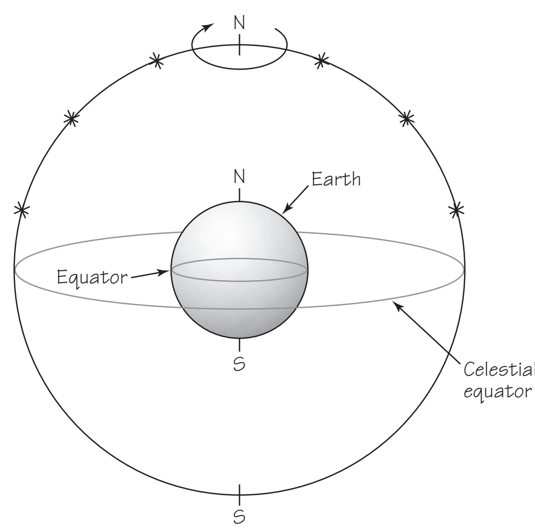


FIGURE 2.7 The celestial sphere and Earth as conceived starting about 500 B.C.

FIGURE 2.8 Geocentric scheme of Petrus Apianus (from his *Cosmographia* of 1551). The Earth is fixed at the center of concentric rotating spheres. The sphere of the Moon ("lune") separates the terrestrial region (composed of concentric shells of the four elements Earth, Water, Air, and Fire) from the celestial region. In the celestial region are the concentric spheres carrying Mercury, Venus, Sun, Mars, Jupiter, Saturn, and the stars.

to the Greeks, is how big the Earth is. Columbus thought it was so small that by sailing west he could reach India more quickly than by traveling east, and thereby find a shorter route for the lucrative spice trade.) Today we know from air travel, satellites, and the impressive pictures of Earth sent back to us from the Moon and outer space that the Earth, our home, can be thought of as a beautiful, round blue ball. But even without airplanes and space flight or sailing trips around the world, we can tell that the Earth really is round—and in the way known to the Greeks over 2000 years ago.

As seafarers, the Greeks knew that when a ship leaving a harbor reaches the horizon, it does not fall over the horizon, but rather it sails out further into the ocean. From the harbor the ship appears to "sink" into the ocean, suggesting that the ship simply goes over the convex curvature of the Earth (see Figure 2.10). Those who traveled in the north–south direction by land or sea noticed that as they traveled north from the equator, the north star (Polaris), which remains fixed over the north pole, seemed to rise in the sky. As Figure 2.11 shows, this could happen only if the Earth is curved outward in the north–south direction. Taking all of these observations into account, people concluded that the Earth must be spherical in shape. These same observations can be made today.

Even though the stars, Sun, and Moon appear to circle around us on the round Earth, someone could still argue that this is just an illusion. The Sun

FIGURE 2.9 Earthrise over moon.

and Moon and stars are really fixed, and it is *we* who are rotating on a north–south axis through the spherical Earth once every day. But there were strong arguments against this interpretation (even though we now know it is the correct one). For instance, common sense seems to tell us that it's impossible for the Earth to be rotating. If the Earth really is a sphere of about 4000 miles in radius (as the Greeks knew), then you can figure out (details in Chapter 3) that people at the equator must be spinning at about 1000 mi/hr through space! Why aren't they hurled off into space, along with assorted animals, rocks, trees, houses, etc? No, common sense seems to agree with the observation that the Earth really is stationary at the center of the Universe and that a celestial sphere carrying the stars and other objects is rotating around it. Anyone who argues differently

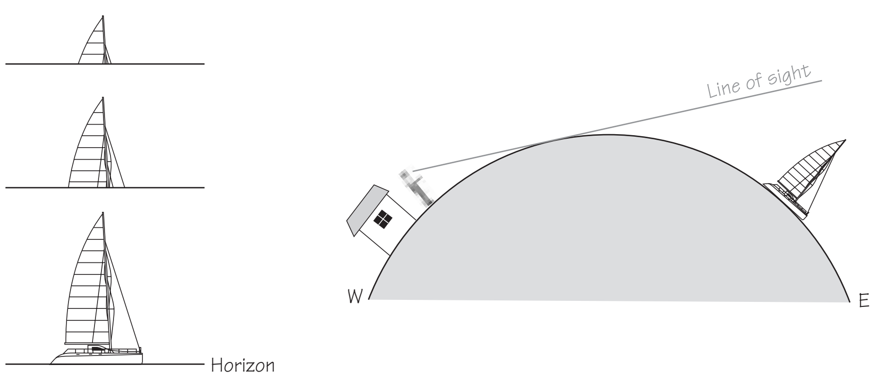


FIGURE 2.10 Ship "sinking" off horizon.

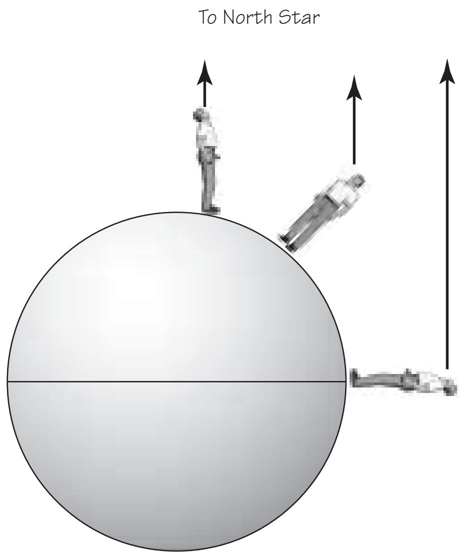


FIGURE 2.11 Observer looking upward towards North Star at three different positions.

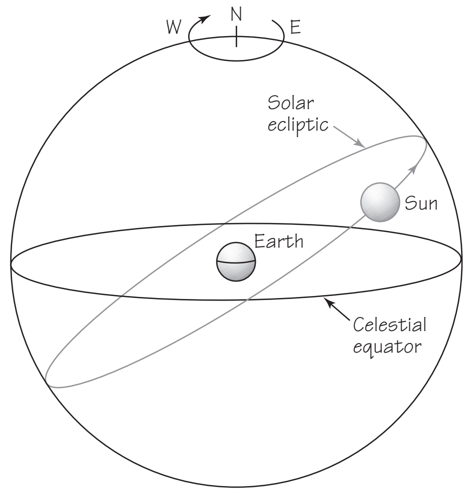
had better have some very good arguments, if they want to convince people that it is really the Earth that is moving and the Sun that is stationary.

The Sun and Seasons

Since each day the position of the Sun, compared with the position of the stars just before sunrise or sunset, appears to have slipped behind the stars 1° per day (actually this observation arises from the Earth's motion around the Sun), the Sun appears to move around the celestial sphere once every year in the backward direction, that is, from the west to the east. This backward motion (relative to the stars) is called "eastward drift." The path—called the *ecliptic*—that the Sun traces out on the celestial sphere is not aligned with anything. Rather, the Sun follows a circle tilted at an odd angle, 23.5°, to the circle formed by our equator and the equator of the celestial sphere, as shown in Figure 2.12. The existence of this tilt is extremely important. It is the origin of the seasons.

Let's look at the motion of the Sun from a place on the northern hemisphere of the Earth (the seasons described here will be reversed for the southern hemisphere). For simplicity we will briefly adapt the Earth-centered view. We will follow the apparent path of the Sun along the path shown in Figure 2.13. At position VE, the Sun is just crossing above the equator, and its rays are hitting equally the northern and southern hemispheres of the Earth. There are exactly 12 hr of daylight and 12 hr of night. The time of year when this happens is called an *equinox*, meaning "equal

FIGURE 2.12 Solar ecliptic vs. celestial equator.



night." Since the Sun is headed higher in the sky above, it passes through the position VE on the celestial sphere; the position VE is called the *vernal (or spring) equinox*. It is the first day of spring, and the beginning of the old astrological calendar year, according to which nature is born anew every spring.

As the Sun appears to move gradually toward the point labeled SS, the days get longer and the nights shorter. The angle of incidence of the Sun's rays on the ground below become more direct and thus cause more heat. When the Sun reaches the position labeled SS, that moment is called the *summer solstice*; it is the first day of summer. From there the days start to get shorter and the nights longer as the Sun moves toward the position AE, the *autumn equinox*. Finally, winter arrives as the Sun travels to its lowest point in the sky at WS, the *winter solstice*, the first day of winter. Now the rays of the Sun at noon come in at

This description is for observers in the northern hemisphere. For observers south of the equator, exchange "north" and "south."

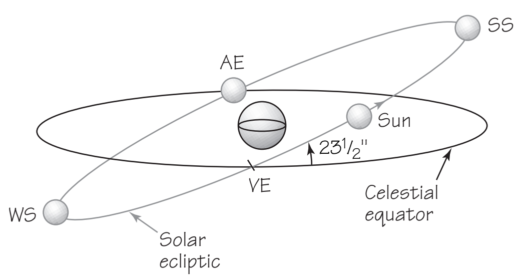


FIGURE 2.13 Diagram showing equinoxes.

the most oblique angle, and leave the ground far less hot than before. The ancient tribes made urgent sacrifices to the Sun at this time in order to induce the sun god not to let the Sun disappear altogether. Apparently the sun god was pleased enough every year to allow the Sun to continue on its journey back to the point VE, where all of nature burst forth once again into a new annual cycle of birth, life, and death.

Notice from Figure 2.13 that at the summer solstice, the point SS, the Sun would be directly overhead at noon to anyone who is 23.5° north of the equator. At the winter solstice, WS, it would be directly overhead at noon to anyone at 23.5° south latitude. The region between these two latitudes is called the *tropic zone*. For those who do not live within the tropic zone, the Sun is never directly overhead at any time during the year. Instead, seen from the northern hemisphere, the Sun reaches its highest point in the sky at noon on the summer solstice, SS, and its lowest point in the sky at noon on the winter solstice, WS. (Your laboratory and demonstration activities may involve your making some of these observations yourself.)

Eclipses and the Phases of the Moon

As discussed earlier, the Moon shares the general east-to-west daily motion of the Sun and stars. But (owing to its own motion around the Earth) the Moon also slips eastward against the background of the stars. It does so much faster than the Sun does, rising each night nearly 1 hr later. When the Moon rises in the east at sunset (opposite the setting Sun in the west), it is a bright, full disk—the "full Moon." Each day after that, it rises later and appears less round. Finally, after about 14 days, it has waned to a thin crescent low in the sky at dawn; when the pale Moon is passing near the bright Sun in the sky and rising with it, you cannot see the Moon at all. At this point it is called "new Moon." After new Moon, you first see the Moon as a thin crescent low in the western sky at sunset. As the Moon moves eastward from the Sun, it gradually fattens until it reaches full Moon again. After full Moon, the cycle repeats itself.

As early as 380 B.C., Plato recognized that the phases of the Moon could be explained by thinking of the Moon as a globe reflecting sunlight and moving around the Earth in about 29 days.

The Moon's path around the sky is very close to the yearly path of the Sun; that is, the Moon is always near the ecliptic. But the Moon's path tilts slightly with respect to the Sun's path. If it did not, the Moon would come exactly in front of the Sun at every new Moon, causing an eclipse of the Sun, a "solar eclipse." In addition, it would be exactly opposite the Sun at every full Moon, moving into the Earth's shadow and causing an eclipse of the Moon, a "lunar eclipse."

(a) (b) (c)

FIGURE 2.14 The Moon as it looks 26 days after New Moon (left); 17 days after New Moon (middle); and three days after New Moon (right). Courtesy of Mount Wilson Palomar Observatory.

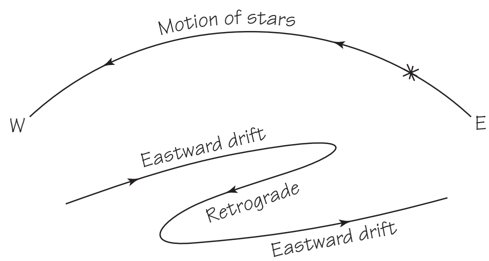


FIGURE 2.15 Diagram of retrograde motion of a planet.

The Planets

Five other objects were also observed on the celestial sphere in antiquity, in addition to the Sun, Moon, and fixed stars. These objects seemed to be stars since, to the naked eye, they appeared as pinpoints of light with no visible disk. But even though they looked like stars, they did not act like stars. As observed over a number of days, a planet, like all other celestial objects, does rise in the east and sets in the west each day, but each day in its rising and setting it falls a few degrees to the east behind the fixed stars, as do the Sun and Moon. This is called "eastward drift." Moreover, occa-

FIGURE 2.16 Babylonian clay tablet recording the observed positions of Jupiter.

FIGURE 2.17 Stonehenge, England.

sionally something very strange happens; the planet appears to speed up relative to the stars and begins moving faster than the stars toward the west, before it settles back into drifting once again toward the east each day. This sudden motion to the west is called "retrograde motion," since the planet seems to be regressing from its eastward drift. In this strange type of motion, the planet forms a looping or S-shaped path against the background of the stars. This apparent motion is now understood, in our present system, in which the Earth and planets orbit the Sun, as an optical illusion (see Figure 2.19b). It occurs whenever the Earth in its orbit passes an outer planet, or an inner planet passes the Earth in its orbit. Because of this seemingly strange behavior, these five objects were called *planets*, which is Greek for "wandering stars." We know today that they are not stars at all but large masses orbiting the sun just like the Earth.

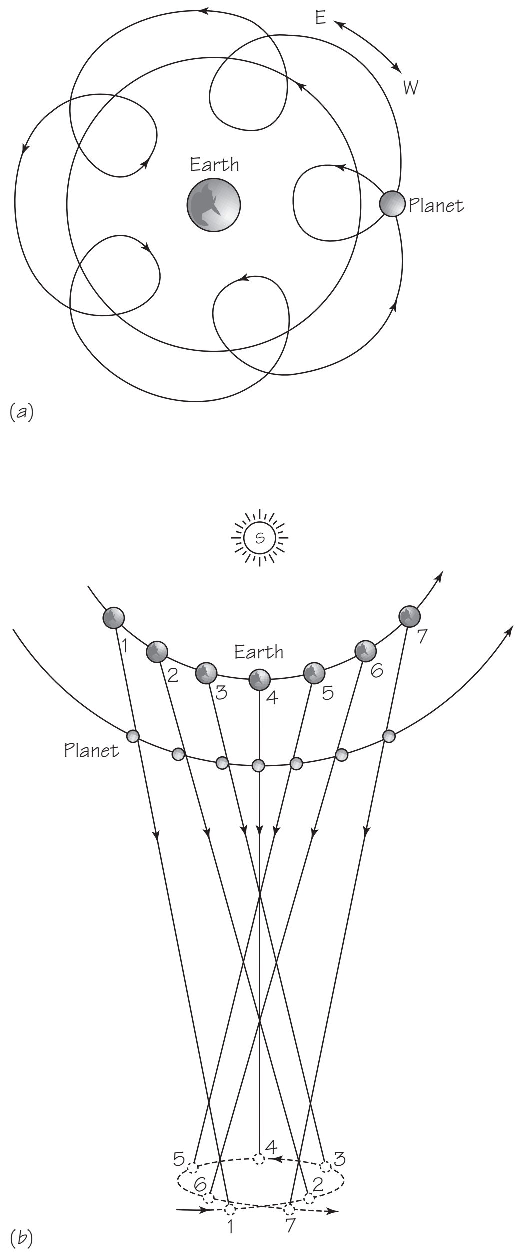
Since the planets seemed to perform their puzzling motion entirely on their own, which only living beings can do, the ancients believed them to be living gods (since they also seemed to be eternal). They also believed that these planet-gods were influential on human affairs. According to the appearance and motions of each planet, the Greeks named the five visible planets for the gods Mercury, Venus, Mars, Jupiter, and Saturn. (There are three other planets, in addition to Earth—Uranus, Neptune, and Pluto. They are not visible without powerful telescopes. Some astronomers do not regard Pluto to be a planet.)

Although the planets were called "wandering stars," they did not wander at random all over the place. They stayed within a narrow band of constellations along the Sun's annual path along the celestial sphere. The ancient Babylonians, who first identified all of our present constellations, also

FIGURE 2.18 Aztec stone calendar.

identified those that lay at that time on the Sun's annual path, the ecliptic. The Greeks called the set of these constellations the *zodiac*. Since the planets stayed within this narrow band of constellations, the zodiac had special significance for ancient believers in astrology. Beginning with our March 21, the first day of nature's "rebirth" in spring, they divided the zodiac into the 12 astrological signs, or constellations, of the zodiac, corresponding to 12 lunar months of about 30 days each. An astrologer could then relate the positions of the planets as they moved within the zodiac to the position of the Sun within each sign of the zodiac, and then pronounce conclusions about human affairs based upon astrological beliefs. As you can see, an astrologer had to be adept at mathematical astronomy, and he would want to see improvements in mathematical astronomy in order to predict the positions of the planets more precisely. But, as noted earlier, there is absolutely no evidence that the planets actually have any effect at all on human affairs. For this reason, the science of astronomy eventually split from the superstition of astrology during the course of the Scientific Revolution.

FIGURE 2.19 Retrograde motion: Ptolemaic (a) and Copernican (b) views.



2.5 COPERNICUS VERSUS PTOLEMY

Long before the time of Copernicus, the Greek astronomer Claudius Ptolemy, who lived in Egypt during the second century A.D. and was related to the Ptolemy dynasty of pharaohs who ruled Egypt at that time, created a mathematical theory, or model, of all of the observed celestial motions outlined in the previous section. In fact, he nearly succeeded in reproducing the exact observations of the celestial motions on the basis of a geocentric model of the Universe. Ptolemy saw his work as a solution to Plato's problem, discussed in the Prologue: to provide a model of the Universe in which all of the observed motions can be explained by referring to combinations of perfect circles rotating with uniform speed.

For instance, Ptolemy's explanation of the so-called retrograde motion of the planets is shown in Figure 2.20. He explained the apparent "looping motion" of the planets by placing the center of one rotating circle, called the "epicycle," which carried the planet, on another rotating circle, called the "deferent," so that together the motions of the two circles, the *epicycle-deferent*, produced the observed looping motion of the planet. By choosing the proper circles and speeds, Ptolemy could reproduce these and other observed motions almost exactly! Moreover, the model accounted for the observation that each planet looks nearer to us (bigger and brighter) while in retrograde motion than when it's not in retrograde, since it is closer to us when it is on the inside of the larger circle.

But think about Ptolemy's theory, indicated in Figure 2.20, as a theory of nature. Is it what you would expect for the actual motion of a planet? Would anyone actually believe that this is the way the planets *really* move? Isn't this just an invention to reproduce the observations without worrying if these are actual motions? Also, aren't there some unresolved problems with this theory, such as: What holds the planet on the epicycle, and what holds the epicycle on the deferent? How can the epicycle cut through the deferent

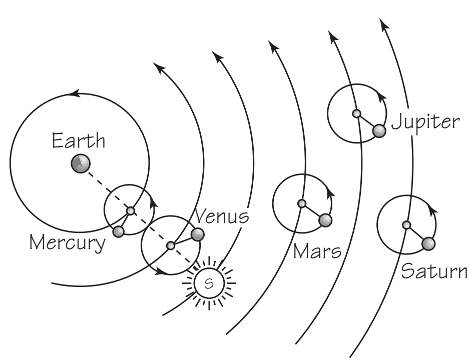


FIGURE 2.20 Simplified representation of the Ptolemaic system.

without breaking it? Moreover, shouldn't all of the circles actually be centered on the Earth? Is this really a satisfactory solution to Plato's problem?

Copernicus did not think so. Raising some of these very same questions in his book, he wrote: "Hence a system of this sort seemed neither sufficiently absolute nor sufficiently pleasing to the mind." Even though it worked, it didn't seem "real" (absolute) to him. Nor was there the harmony, simplicity, or "beauty" to Ptolemy's system that Plato had believed to exist in nature. It wasn't "pleasing to the mind." So Copernicus began looking for an alternative. Apparently he found encouragement in an alternative that had already been considered and rejected in ancient times because it was not fully worked out. Copernicus revived an old proposal (attributed to the Greek Aristarchus, ca. 281 B.C.) in which it is the Earth that moves, while the Sun and stars remain fixed. And he fully developed it into the first viable alternative to Ptolemy's system in 1400 years! In its basic features, it is the system we use today.

Copernicus's Alternative

Instead of interpreting the motions of the celestial objects as revolving around the fixed Earth each day from east to west, Copernicus realized that these observed motions would appear exactly the same for an observer on the Earth *if the Sun and stars are stationary and it is the Earth that rotates on its axis once a day from west to east.*

Copernicus had discovered an ambiguity in the concept of relative motion. Think about this for a moment. As suggested earlier, we can see the Sun rise in the east every morning, but is it the Sun that is rising from the fixed eastern horizon, or is it the horizon that is falling away as the Earth rotates, while the Sun remains fixed? Ptolemy and most people believed the former, Copernicus argued the latter. The Earth, he stated, is rotating west to east while the Sun remains stationary in space. Because the apparent motion of the Sun is an example of relative motion—motion that is relative to an object that itself may in fact be in motion—all of the celestial observations would be exactly the same in either view.

In addition, instead of placing the Sun on a circle centered on the Earth, he realized that the annual path of the Sun against the background of the stars could be obtained equally well by *placing the rotating Earth on a circular orbit that revolves around the stationary Sun once every year*. Our seasons, as caused by the annually changing position of the Sun in the sky, he said, are due to the tilt of the Earth's axis from the perpendicular to the plane of its orbit—not the tilt of the Sun's path (the ecliptic) from the perpendicular to the plane of the Earth's equator. The Earth's tilted axis gives us the seasons. As the Earth orbits the Sun each year, the north pole always

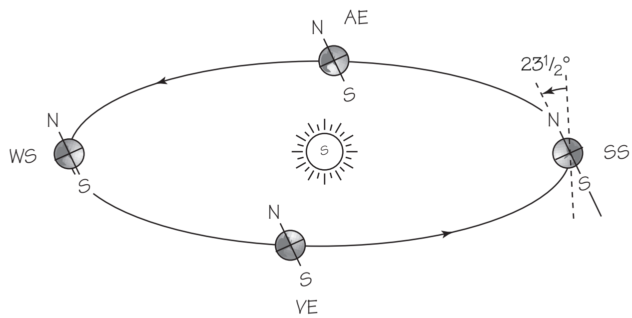


FIGURE 2.21 Copernican view of Earth's revolution about the Sun.

points toward the star Polaris—the "north star"—no matter where the Earth is on its orbit (see Figure 2.21).

In Copernicus's system, only the Moon orbits the Earth, as the Earth orbits the Sun. The Sun remains stationary. (We now know that the Sun too is moving as part of our rotating galaxy, which, in addition, is moving away from other galaxies as the Universe expands. But this does not change the observations within the solar system of planets.) The other planets then also orbit the Sun in the order they are known to have today: Mercury, Venus, Earth, Mars, Jupiter, Saturn (and, as later discovered, Uranus, Neptune, and Pluto). This entire system is called a *heliocentric system* or a *solar system* ("sol" means "sun" in Latin), because the Sun is at the center.

To see how well the new perspective accounts for the observations of the seasons, let's compare the seasons as observed from the moving Earth with the seasons as observed from the perspective of a stationary Earth (review the description in "the Sun and seasons" in Section 2.4). We will be in the northern hemisphere of the Earth and observe the Sun at noon every day as the Earth orbits the Sun once a year, starting from the point labeled VE in Figure 2.13. At this point the Sun's rays are hitting equally the northern and southern hemispheres of the Earth, so this is the Vernal Equinox. In this part of the orbit, as the Earth turns each day, the Sun remains longer in view, and the Sun's rays hit the northern hemisphere more directly. The Earth is heading into summer.

As the Earth moves on its orbit toward the position labeled SS, the north pole of the Earth always remains pointed toward Polaris, so the northern hemisphere begins to tilt toward the Sun: the days grow longer and the nights grow shorter. The position SS is the Summer Solstice, or the first day of summer. From there the days start to get shorter and the nights longer as the Earth moves to AE, the Autumn Equinox. Finally, as the Earth moves into the part of its orbit where the northern hemisphere is tilted away from the Sun, the days get shorter, the nights longer, the rays of the Sun are less direct, and the Sun does not rise as high in the sky as seen by an observer on the Earth. This is winter, and the point WS is the Winter Solstice. After that, the Earth continues on its journey to the Vernal Equinox when the entire cycle is repeated for another year.

You can see from this that, as far as the seasons are concerned, Copernicus's heliocentric theory is just as capable of explaining the observations as is Ptolemy's geocentric theory.

Copernicus's Solar System of planets, including the Earth as the "third rock" from the sun, also provided a wonderfully simple explanation for the puzzling motion of the planets, and without Ptolemy's fictitious circles upon circles. In accounting for retrograde motion, Copernicus replaced all five of the planets' major epicycles with a single circle: the Earth's orbit around the Sun. The numbered lines in Figure 2.19b indicate the lines of sight from the Earth to an outer planet. Most of the time, the outer planet appears to be moving normally on its path against the background of the stars (eastward drift). But the path that we see from the Earth gradually begins to change as the Earth catches up to and passes the outer planet. If you

FIGURE 2.22 Page from *On the Revolutions of the Heavenly Spheres* showing the solar system according to Copernicus. Courtesy of Jagiellonian Library, Krakow.

follow the progression of the lines as the Earth passes the planet, you will see a simple explanation of the observed retrograde motion. The planet *seems* to "regress" (move west) for a while then proceed again to the east, creating the appearance of a looping motion, simply because we are passing the planet as the Earth moves along in a different orbit. Since the Earth and the planet are at their closest approach to each other when retrograde occurs, the planet looks bigger and brighter because it is nearer to us. The same thing occurs with the observed retrograde motion of an inner planet, Venus or Mercury, only in this case it is the inner planet that is passing us. (However, it should be noted that, in the end, Copernicus found it necessary to reintroduce small epicycles for each of the planets in order to account for the nonuniformity of each planet's motion around the Sun.)

Once again, the two perspectives involved in relative motion are at work: either the planets can be considered to be moving, while the Earth is at rest, or the Earth can be considered to be moving, while the regressing planet is also moving but at a different speed as seen from the fixed Sun. Without further information, both views are equally valid. As a result, we now have two radically different yet equally capable explanations for one set of observations: Ptolemy's geocentric theory and Copernicus's heliocentric theory. Both of these are equally viable, and so far neither one has a clear advantage over the other.

2.6 ARGUMENTS FOR THE HELIOCENTRIC SYSTEM

You can see how revolutionary Copernicus's ideas were. The centuries-old geocentric system was now, for the first time, under serious challenge by the completely different heliocentric system proposed by Copernicus. Most new theories in science arise from new experimental evidence indicating that the current theory needs to be drastically revised or even replaced by a new theory. However, in this case, there was no new observational evidence leading Copernicus to suggest his new theory. Instead, for him, and for the few others who followed him at first, the most important arguments in its favor were those emphasized centuries earlier by Plato and the Pythagoreans—beauty, harmony, and simplicity.

Like Ptolemy and other mathematical astronomers, Copernicus followed Plato in attempting to account for the observed data in terms of simple mathematical (geometrical) relationships underlying the observations. Copernicus was trying to solve Plato's problem on the basis of motions that were perfectly circular and with perfectly uniform speed, but without resorting to some of the imaginary circles-upon-circles that Ptolemy had introduced to make his theory work. The resulting alternative to Ptolemy's theory could do everything that Ptolemy's theory could do in reproducing the quantitative observations—but no better, nor no worse. Most times scientists have only one theory to account for the observed data; this time they had two equally viable, yet incompatible contenders for the same set of data!

But Copernicus did not stop there. He pointed out what he believed to be the simplicity, harmony, and "beauty" that Plato required of any theory of nature. The theory was simple because Ptolemy's circles-upon-circles and similar contrivances were no longer necessary (except when he got to the finer details of the system); just the rotation of the tilted Earth and the orbits of the Earth and planets were all that were needed to obtain the main observations.

The heliocentric theory had the advantage for Copernicus that it placed the Sun—the symbol of truth and divinity, the giver of light, warmth, and life—in a privileged position. In a statement worthy of a true follower of Plato, some of whose ideas bordered on Sun worship, Copernicus proclaimed in his book:

> In the midst of all, the Sun reposes, unmoving. Who, indeed, in this most beautiful temple would place the light-giver in any other part than whence it can illumine all other parts? . . . So we find underlying this ordination an admirable symmetry in the Universe and clear bond of the harmony in the motion [period] and magnitude [radius] of the spheres, such as can be discovered in no other wise.

The Sun at the center provided a focus to the entire system. As the quotation indicates, there was also a numerical harmony that Copernicus saw in his system when he considered that not only the Earth but all of the other five visible planets also revolved around the Sun. Assuming that all of the observed motions involve primarily perfect circles and uniform speeds, Copernicus used the simple geometry of circles and tangents to determine the radii and periods (time for one revolution) of the orbits of the planets around the Sun as seen from a rotating, orbiting Earth. Analyzing the data on the planets' orbits that had been gathered for centuries, Copernicus used the Earth's day and year as measures of time and the Earth's orbital radius as the unit of distance. Since he didn't know how large the Earth's orbital radius actually is, it could be called one astronomical unit, or 1 AU. This is still used today as a convenient measure for distances within the Solar System. Not only was Copernicus the first to obtain the present-day order of the planets—which Ptolemy did not know—but his results were very close to the modern values for the orbital periods and rel-

FINDING THE RELATIVE RADIUS OF A PLANET'S ORBIT

Let angle *SEP* be the angle of maximum "elongation" of the planet, say Venus, away from the Sun, as viewed from the Earth. Line segment *PE* is then a tangent to the circle of the orbit of Venus. So angle *SPE* must be a right angle. Hence the ratio *SP/SE* must be equal to the sine of the angle *SEP*. Angle *SEP* was observed to be 46°, so

$$\sin 46° = 0.72 = SP/SE.$$

Copernicus defined the distance from the Sun to Earth, *SE*, to be 1 AU. So the distance from the Sun to Venus, *SP*, is 0.72 AU.

A direct observation of the maximum elongation of Mercury or Venus can therefore be used to compute the relative radius of each of these planets. The relative distances of the outer planets from the Sun can be found by a similar, but somewhat more complicated, method.

Modern tables of planetary positions as seen from the Earth are computed from a geocentric model using mathematical techniques that might be considered the equivalent of Ptolemy's epicycles. (See, for example, T.S. Kuhn, *The Copernican Revolution*, pp. 175–176.)

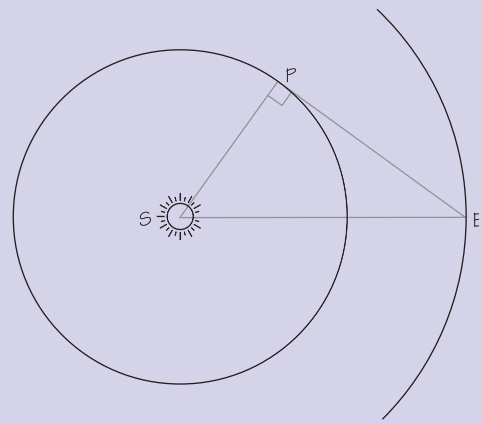


FIGURE 2.23 Method for computing distances.

ative radii of the planets (as well as the Sun and stars at the two extremes), which are given in the table below. (See the insert for an example of how Copernicus obtained the radius of Venus in relation to the radius of the Earth's orbit.)

Object	*Period*	*Radius of Orbit (in AU)*
Sun	0.00	0.00
Mercury	87.97 d	0.39
Venus	224.70 d	0.72
Earth	1.00 yr	1.00
Mars	1.88 yr	1.52
Jupiter	11.86 yr	5.20
Saturn	29.46 yr	9.54

The above table exhibits the harmony that Copernicus so admired in the heliocentric system. Notice that, starting from the Sun, as the relative radii get larger so do the periods for all of the planets, right out to the stars.

This may seem obvious to us today, but for Copernicus, who was the first to notice this relationship, such harmony and simplicity of his system were not merely convenient but also "pleasing to the mind," and therefore an indication of truth. The pleasure which scientists find in the harmony and simplicity of their models is one of the most powerful experiences in science. For instance, one of the leading physicists of the twentieth century, Richard P. Feynman, has written:

> What is it about nature that lets this happen, that it is possible to guess from one part what the rest is going to do? That is an unscientific question: I do not know how to answer it, and therefore I am going to give an unscientific answer. I think it is because nature has a simplicity and therefore a great beauty.*

2.7 ARGUMENTS AGAINST THE HELIOCENTRIC SYSTEM

Not everyone prized the harmony, beauty, and simplicity that Copernicus saw in his new theory. Such aesthetic qualities were not enough to convince anyone who did not think this way. What was also needed was hard evidence about a crucial difference, yet there was no outstanding hard observational evidence that pointed to the heliocentric theory and away from the geocentric theory. Even worse, there were extremely powerful arguments against such a revolutionary idea as a rotating and revolving Earth.

First of all, as noted earlier, simple common sense seems to tell us that the Earth cannot be moving. And a moving Earth would raise a host of excellent questions, such as, if the Earth is spinning on its axis once a day, then why don't objects fly off it? Why aren't there perpetual hurricane-force winds sweeping across the surface of the Earth due to its rotation? Why aren't birds swept from the sky? We now have answers for all of these questions (mainly by using Newtonian mechanics, as we shall see). Copernicus himself attempted to answer some of them, but he worried greatly that, because of such "common-sense" questions, when he published his new theory people "will immediately shout to have me and my opinion hooted off the stage. For my own works do not please me so much that I do not weigh what judgments others will pronounce concerning them." Perhaps for this reason he waited until he was in failing health before publishing his book.

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* R.P. Feynman, *The Character of Physical Law* (Cambridge, MA: MIT Press, 1967), p. 173.

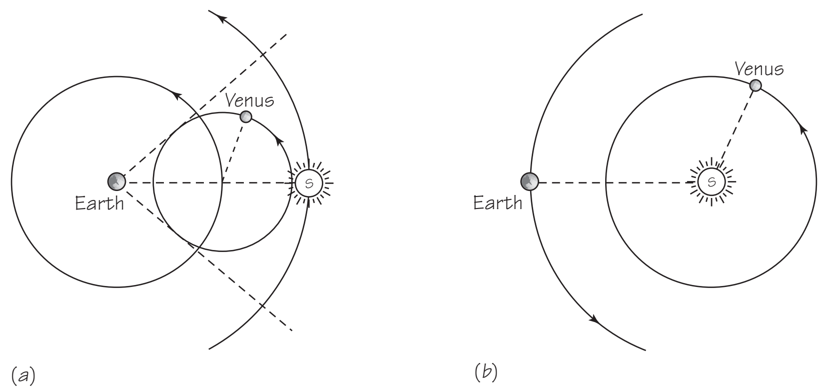


FIGURE 2.24 Changing the frame of reference from Earth to Sun: (a) Venus as seen from a stationary Earth; (b) Venus as seen from a moving Earth in a heliocentric system.

Second, the heliocentric model raised questions about certain natural phenomena. For instance, how does a falling stone know where to land, if the Earth is in constant motion? One of the most cogent of such questions concerned what is known as *stellar parallax*. Why don't the stars appear to shift in the sky if we see them from different angles as we orbit the Sun, much as the angle to an object in the distance shifts as we move our position? If the Earth is indeed revolving around the Sun, as in Figure 2.25c, then the angle representing the position of a star in the sky as seen from the Earth should gradually shift during the course of a year, as the Earth moves along its orbit. However, careful observations made at that time yielded no such shift in the angle of any star; no stellar parallax could be observed. Hence, many concluded, the Earth cannot be orbiting the Sun. Of course, we know today that the Earth is indeed orbiting the Sun, and Copernicus and his followers would have responded with the answer we have today: the stars are so far away from the Earth and Sun that this effect cannot be observed without powerful telescopes. In other words, if Figure 2.25c were drawn to scale, the orbit of the Earth would appear as a dot on the page, and the parallax effect would be impossible to discern. To this argument, Copernicus's contemporaries responded by wondering why God would waste his creative power in creating so much empty space between the Earth and the stars, when much less will do.

Third, in addition to these arguments, there were also major philosophical objections to the heliocentric model. Ptolemy's theory had 1400 years of tradition behind it and Aristotle's Earth-centered cosmology to back it up. Aristotle's entire cosmology, which was the "world view," or

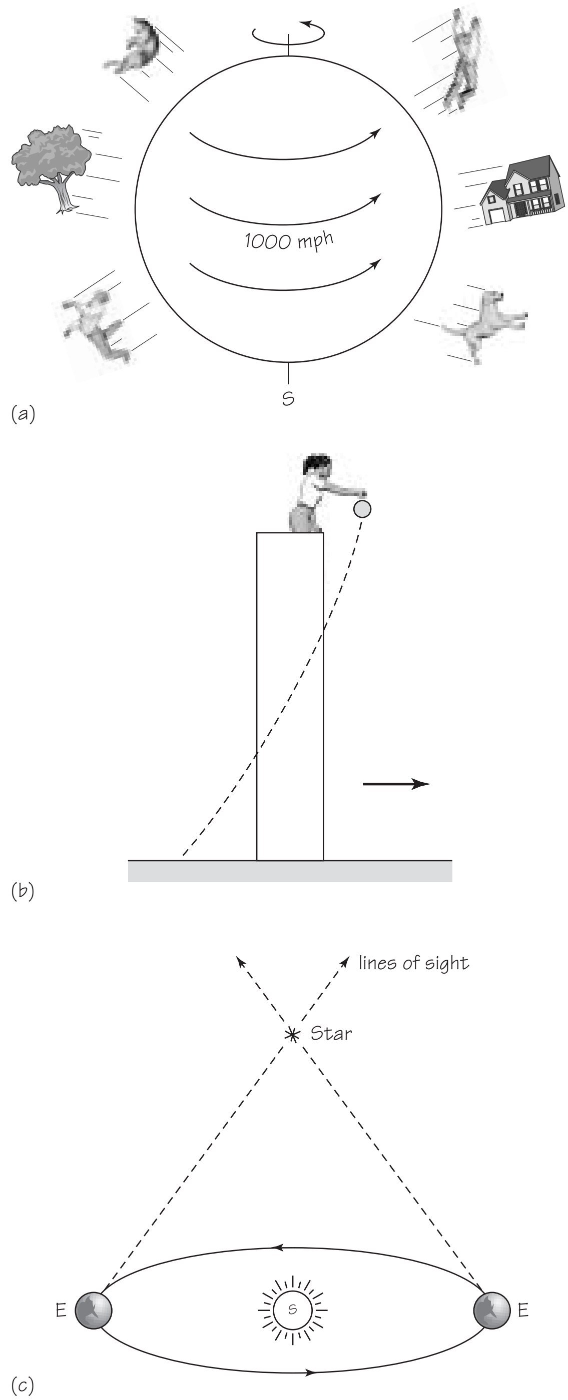


FIGURE 2.25 Arguments against the heliocentric system. (a) refers to the rapidly spinning Earth; (b) what was believed to happen if a ball is dropped from a tower as the Earth moves; (c) the supposed shifting position of a star as seen from the moving Earth.

philosophical outlook, of the day, would collapse if the Earth is not at the center of the Universe and if the celestial sphere of stars and planets is not moving. How will the four elements know their proper place if the Earth is not at the center? Moreover, if the Earth is also a planet, then should the realm of the eternal heavens now be considered imperfect, as is the Earth?

Fourth, there were no clear scientific advantages to Copernicus's theory over Ptolemy's—nor was Ptolemy's theory any better at explaining the observations than Copernicus's theory. No known observation or prediction of planetary position was explained by one system and not by the other. Copernicus had a different viewpoint, as equally well-argued as Ptolemy's, but it was no better than Ptolemy's in predicting the precise positions of the planets, and precision was necessary for the astronomers, astrologers, and calendar-makers of the day. Nevertheless, Copernicus's theory was easier to use, so some astronomers used Copernicus for their calculations but, nevertheless, they continued to believe in the systems of Ptolemy and Aristotle.

Finally, Copernicus's challenge to Aristotle's cosmology also brought his theory sooner or later into conflict with the religious authorities, not only regarding the vastness of outer space. Most learned Europeans at that time recognized the Bible and the Church Fathers on the one hand, and the writings of Aristotle and his followers on the other hand, as the two supreme sources of authority, and both seemed to agree that we humans living on the Earth are at the center of Creation. Copernicus was now attempting to displace the Earth and human beings from the center, rendering the Earth merely the third of six visible planets orbiting a fiery object, the Sun. As a result, many scholars and all of the religious faiths in Europe, including the new Protestants, sooner or later opposed Copernicus. They used biblical quotations (e.g., Joshua 10:12–13) to assert that the Sun and Moon are moving and that the Divine Architect must have worked from a Ptolemaic blueprint. In 1616 (during the Counter Reformation), the Inquisition placed Copernicus's book on the *Index of Forbidden Books* as "false and altogether opposed to Holy Scriptures." Some Jewish communities also prohibited the teaching of Copernicus's theory. Since one of the results of science is a change in knowledge about ourselves and our place in the Universe, it sometimes happens that we don't like what we discover. In fact, often the more we learn about our world, the humbler our place in it seems to be. Many times this results in cultural and religious upheaval and even in attempts to suppress the new theories.

In short, the Sun-centered Copernican scheme was scientifically equivalent to the Ptolemaic scheme in accounting for the observed motions of celestial objects in terms of perfect circles turning at uniform speeds. It had the advantage over the Ptolemaic system in its simplicity, harmony, and beauty, but little else. At the same time, important arguments of science, common sense, and belief were raised against it. The bottom line: There were now two equally viable yet incompatible theories for one set of data; and one theory (Ptolemy's) was in accord with tradition, common sense, and everything people believed at the time about themselves and the Universe in which we live.

Nevertheless, as we have long since discovered, and by arguments we shall encounter later, Copernicus was indeed right:

> The Sun *is* at the center of the solar system, the Earth *does rotate* on its axis once a day, and the Earth and planets *do orbit* the Sun.

But at that time the theory seemed false, absurd, and even dangerous.

2.8 CARRYING FORTH THE REVOLUTION

Following Copernicus's death, many astronomers regarded his heliocentric model as a useful hypothesis for calculations, but most people rejected it

FIGURE 2.26 Tycho Brahe's observatory on the island of Hven.

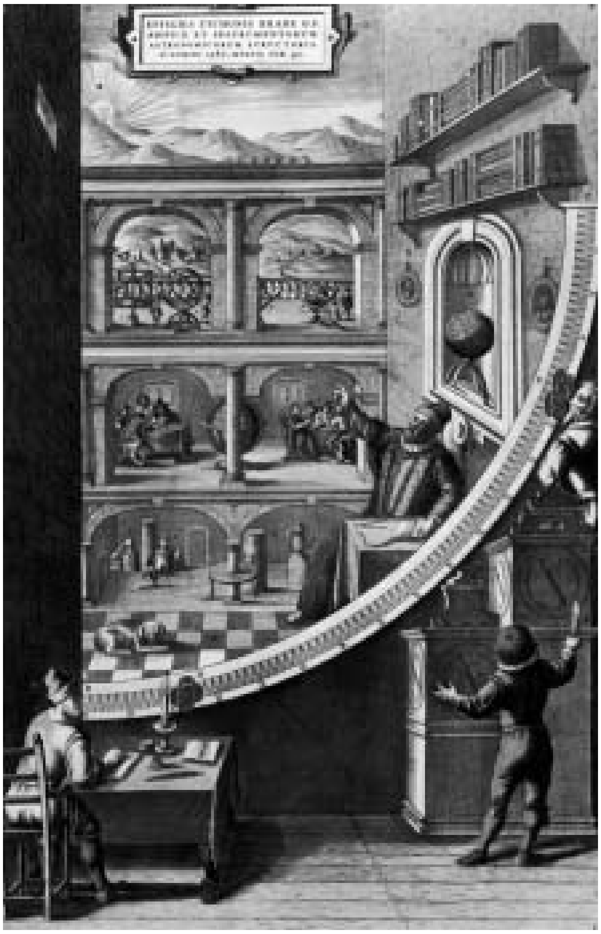


FIGURE 2.27 The hall containing Tycho Brahe's great quadrant. The rest of the laboratory is shown, with Brahe making an observation (aided by assistants).

as a physical reality. There was no instant revolution. In fact, it took nearly a century and a half of further hard work and brilliant discoveries to dismantle the geocentric theories of Aristotle and Ptolemy and to build up the heliocentric system of today, and with it the physics of today, piece by piece.

Looking back on the period after Copernicus, we can see that Copernicus's ideas about truth and beauty, although important then and now, were simply not enough to induce people to switch suddenly to a radically different point of view, even if, as we now know, it was the correct one. What was needed to accomplish the transition to the heliocentric system was further *scientific evidence*. First, much more precise astronomical data were needed that would enable astronomers to decide between these two theories. Up to that point in time, the available data that had been used for centuries were too imprecise to enable a decision one way or the other.

Fortunately, Tycho Brahe, the greatest observer before the invention of the telescope, was able to provide such data within a few decades after Copernicus's death.

Second, mathematical analysis of Brahe's data was necessary in light of the two competing celestial theories. It was again fortunate that Brahe's data came into the hands of one of the greatest mathematical astronomers, Johannes Kepler. Kepler's lifelong analyses of Brahe's data resulted in new laws of planetary motion that went far beyond Plato's simple assumptions of perfect circles turning at constant speeds.

Third, a new understanding of motion on the Earth was also needed, and this was provided in large part by Galileo and Newton.

Fourth, since science is also a cultural phenomenon, the educated public needed to be brought behind the new theory, and new generations educated into the new theory, and this began to occur through Galileo's popular writings on his sensational discoveries with the telescope.

Finally, we can see that all of these aspects, and many other elements, had to come together into a new alternative for a unified view of nature, to replace the Aristotelian world view. This Isaac Newton provided in one of the greatest scientific books ever written, *Philosophiae Naturalis Principia Mathematica* (1687), usually refered to as the *Principia* or the *Mathematical Principles*, in which he presented a unified theory of the physical world united by the law of universal gravitation. Looking back over his work and that of his predecessors, Newton once wrote to a friend that if he had been able to see farther than others it was because he had been standing on the shoulders of giants.

Let's look closer at some of these giants.

2.9 NEW DATA

Tycho Brahe was born in 1546 of a noble, but not particularly wealthy, Danish family. By the time he was 14 he had become intensely interested in astronomy. Although he was studying law, the studious lad secretly spent his allowance on astronomical tables and books. Later he observed a bright nova, or new star (actually it was a supernova, which is an exploding star). It appeared in the constellation Cassiopeia, then faded over several years. He also observed a comet that he determined to be at least several times farther away from the Earth than the Moon. Aristotle and the ancients had taught that all change must occur below the Moon, while the region beyond the

> Although there were precision sighting instruments, all observations were with the naked eye. The telescope was not to be invented for another 50 years.

FIGURE 2.28 Tycho Brahe (1546–1601).

FIGURE 2.29 A comet like the one Brahe observed in his student days.

Moon is perfect, therefore unchanging. Yet here were two events that indicated that the heavens do change! Evidently at least one assumption of the ancients was wrong; perhaps other assumptions were wrong, too.

As a student, Brahe had read the works of both Ptolemy and Copernicus. Soon he discovered that both men had relied upon tables of observed planetary positions that were not very accurate. He concluded that astronomy needed a complete new set of observations of the highest possible precision, gathered over many years. Only then could a satisfactory theory of planetary motion be created. He decided to devote his life to the task.

With the support of the King of Denmark, Brahe set up the first state-sponsored astronomical observatory, from which he made daily readings of the positions of all of the planets and all visible celestial objects. With state funding, able assistants, and his mechanical skill, Brahe greatly improved the available astronomical instruments, chiefly by making them much larger. This was before the invention of the telescope, so observations did not involve magnifying the observed objects. Instead, the goal was to mea-

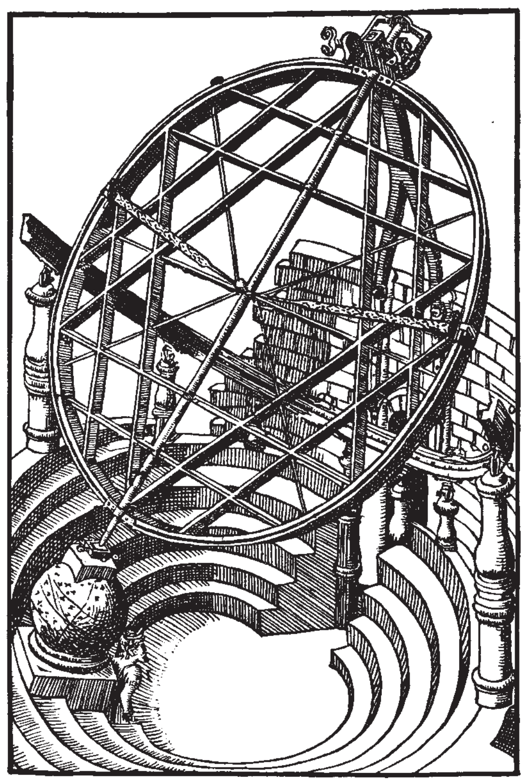


FIGURE 2.30 One of Tycho Brahe's sighting devices. Unfortunately, all of Brahe's instruments were destroyed in 1619 during the Thirty Years' War.

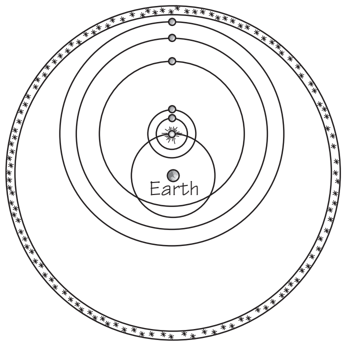


FIGURE 2.31 Main orbits in Tycho Brahe's system of the Universe. The Earth was fixed and was at the center of the Universe. The planets revolved around the Sun, while the Sun, in turn, revolved around the fixed Earth.

sure the position of the celestial objects in the sky as precisely as possible. The larger the measuring instrument, the more precise the angles of the object's position against the background of the celestial sphere could be read. Some of Brahe's instruments were huge. For instance, one of his early instruments was so large that it took several workers to set it into position; but readings with it were accurate to within two minutes of arc. The data Brahe compiled during his decades of nightly observations with these instruments constituted the most accurate measurements of planetary positions ever assembled up to that time.

Four years before his death in 1601, Brahe moved from Denmark to Prague, where the Emperor of Bohemia promised him new support. Not being a mathematician himself, since he was trained in law, Brahe hired a recently graduated German mathematical astronomer, Johannes Kepler, to begin analyzing his years of data in order to decide among the opposing theories of the solar system. There were by then *three* candidates: Ptolemy's geocentric theory, Copernicus's heliocentric theory, and a hybrid "compromise theory" proposed by Brahe himself.

According to Brahe's proposed theory, the planets orbit the Sun, but the Sun orbits the stationary Earth (see Figure 2.31). It was a lawyer's brilliant compromise: it maintained the harmony of the planetary orbits and a privileged position for the Sun, but it also maintained the stationary Earth. Many researchers who liked the harmony of Copernicus's theory, but could not yet accept the moving Earth, welcomed Brahe's compromise as an intermediate theory. It eventually served as a stepping stone from Ptolemy to Copernicus.

When Brahe died unexpectedly in Prague in 1601, a court battle ensued between Kepler and Brahe's heirs over possession of Brahe's lifelong data. Kepler won out in the end. Fortunately for the future of science the data compiled by the world's greatest naked-eye observer now fell into the hands of the world's greatest mathematical astronomer of the day.

2.10 NEW ORBITS

Johannes Kepler (1571–1630) was born into a Protestant German family known equally for its dysfunction as for its mysticism. His mother was accused of being a witch. His father narrowly escaped hanging and later abandoned the family. Kepler attended the University of Tübingen where he studied mathematics, which at that time encompassed mathematical astronomy. Greatly moved by Plato as well as Protestant theology, Kepler became convinced of the Copernican system, in part because he believed that the Sun is the symbol of God and must therefore be at the center of the Universe. Moreover, like Plato, he believed not only that God had used mathematical principles to create the Universe, but also that God and mathematics were in fact identical: "Why waste words?" he wrote. "Geometry existed before the Creation, is coeternal with the mind of God, is God Himself." Kepler became the first astronomer to support Copernicus publicly.

After graduating, Kepler worked as a mathematics teacher, calendar maker, and (to make ends meet) as a court astrologer. He devoted himself to an attempt to discover what he called the "cosmic mystery," the geometrical blueprint according to which God had created the solar system. He wanted to know the mathematical reasons why there are six, and only six, visible planets (the three others being discovered later), and why the planets are in the precise orbits they currently occupy. There must be an undiscovered harmony that accounted for this, he reasoned, since God does nothing by chance. Kepler thought he found the answer to his questions in the five regular solids, also known as the "Platonic solids." Look back at the five regular solids (shown in the Prologue) that Plato had used to account for the five elements. Kepler believed that there are six planets, and only six planets, because God had set up the solar system so that these five solids fit within the five spaces between the six planets. By trial and error, Kepler found that within about 5% accuracy the six planetary orbits could be fit within and around the five solids if they are taken in order of size, as shown in Figure 2.32.

Kepler's idea of using Plato's solids to explain why there are six, and only six, planets (published in 1597) sounds eccentric today, but it was an ingenious one for its time, and it demonstrated Kepler's mathematical capabilities. In fact, Brahe was so impressed by Kepler's abilities that he hired the young man as his assistant. At Brahe's request, Kepler set to work on a careful analysis of the orbit of just one planet, Mars, searching for the geometrical figure

> In keeping with Aristotelian physics, Kepler believed that force was necessary to drive the planets along their circles, not to hold them in circles.

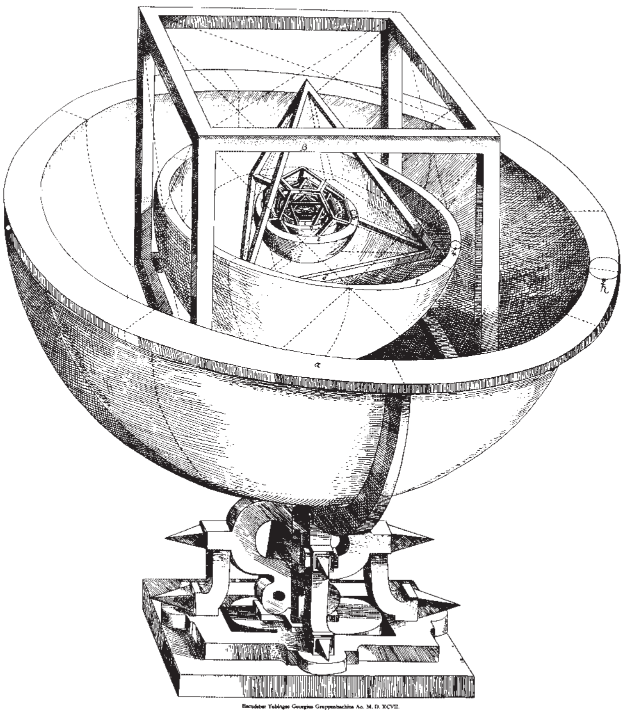


FIGURE 2.32 Kepler's model from *Mysterium Cosmographicum* explaining the spacing of the planetary orbits by means of the regular geometrical solids. Notice that the planetary spheres were thick enough to include the small epicycle used by Copernicus.

that best represented its orbit. Once he found the best fit, he might then be able to apply this geometrical figure to describe better the orbits of the other planets. This would ultimately lead, he hoped, to an understanding of the hidden harmony behind the orbits of the entire solar system.

Kepler naturally began by attempting to fit a circle to the orbit of Mars as seen from the supposed circular orbit of the Earth. He displayed extraordinary tenacity in the work, for after 70 attempts spanning five years, all done by tedious pen-and-paper calculations (of course, no hand calculators or computers in his day!), he was still no closer to the solution. In a book on the eventual solution, titled *New Astronomy*, in 1609, he painfully described every dead-end for his readers, then he wrote:

> If thou, dear reader, art bored with this wearisome method of calculation, take pity on me who had to go through with at least seventy repetitions of it, at a very great loss of time; nor wilst thou be surprised that by now the fifth year is nearly past since I took on Mars.

Fortunately, Kepler had made a major discovery earlier that was crucial to his later work. He found that the orbits of the Earth and other planets were in planes that passed through the Sun. Ptolemy and Copernicus required special explanations for the motion of planets north and south of the ecliptic, but Kepler found that these motions were simply the result of the orbits lying in planes tilted to the plane of the Earth's orbit.

The difficulty for Kepler was that he could make the orbit almost fit a circle—*but not quite*. It fit a circle to within an accuracy of about 8′ of arc. This was better than the fit to any previous data, but Kepler knew that Brahe's data were even more accurate than this, to within 2′ of arc. To his credit, Kepler reluctantly gave up his commitment to circular orbits, and with it over twenty centuries of tradition. After further tedious calculations, Kepler finally arrived at a result that was so universal that it is called a "law of nature."

A *law of nature* is different from a *theory*, since a theory encompasses data and assumptions and hypotheses that can in principle be altered and improved or abandoned as new data and ideas become available. A scientific law is a statement about nature. It can be accepted or rejected, and sometimes expanded to include other circumstances, but it does not contain hypotheses or assumptions. Kepler's laws of planetary motion are still valid today for planets, moons, satellites, and any object orbiting any other object under the action of gravity. But these laws must be modified slightly to take into account additional effects due to gravity and relativity theory.

The First Law

What Kepler discovered from his analysis of Brahe's data is that the planets do not orbit on circles but on *ellipses*. Kepler's result was the first of what we now call Kepler's three laws of planetary motion. They are still valid today.

> Kepler's first law of planetary motion, the law of ellipses: *The planets orbit the sun on ellipses, with the sun at one focus and nothing at the other focus*.

Kepler was fortunate to have chosen Mars for analysis. Its orbit is the second most elliptical among the planets then known. If he had chosen Venus, which is nearly circular, he would not have obtained the First Law.

What is an ellipse? You may have learned in geometry that an ellipse can be drawn when a string is attached to two points and then stretched taut by a pencil. As the pencil moves, it traces out an ellipse (Figure 2.33). The two points, F_1 and F_2 are called the foci (singular: focus). If there are walls around the edge of the ellipse, sound or light emanating from one focus will bounce around the ellipse and

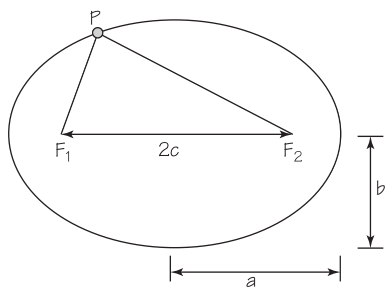


FIGURE 2.33 An ellipse.

eventually converge at the other focus. The closer the foci are to each other, the closer the ellipse comes to being a circle. The farther apart they are, the flatter the ellipse, until finally a straight line is formed. The amount of "flatness" of an ellipse is known as its eccentricity. A measure of the eccentricity of the ellipse is the ratio of the distance F_1F_2 and the long axis of the ellipse. If we call the distance between F_1 and F_2 $2c$, and if we call the length of the long axis $2a$, then the eccentricity e is defined by the equation $e = c/a$. If c is zero, the foci are together and the eccentricity is zero; the ellipse is a perfect circle. Also note that the greatest possible eccentricity for an ellipse is $e = 1.0$. In this case, the ellipse becomes so flat that it approaches a straight line.

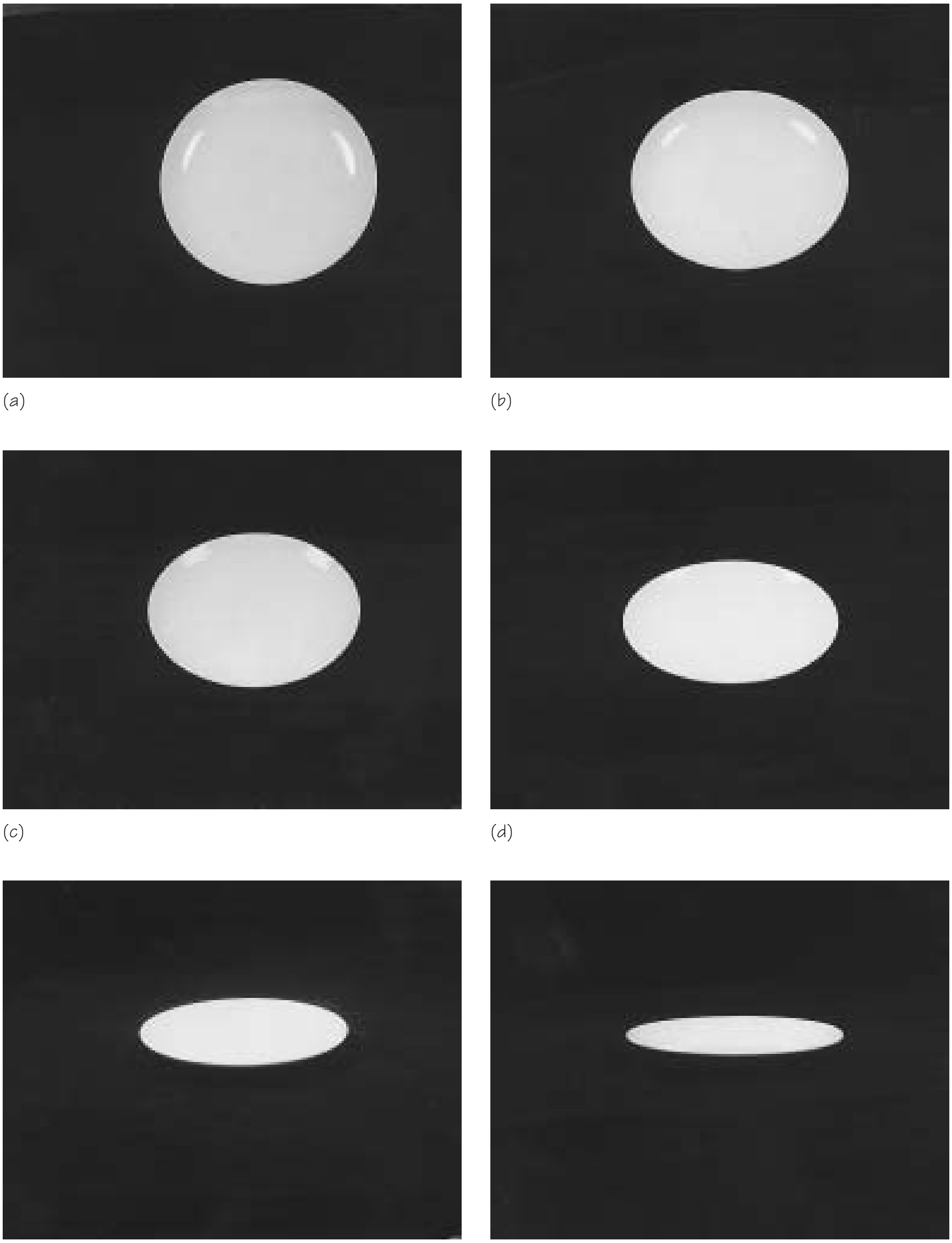
Eccentricities of the visible planets	
Mercury	0.206
Venus	0.007
Earth	0.017
Mars	0.093
Jupiter	0.048
Saturn	0.056

Note that all of the orbits are nearly circular except for Mercury's.

We have since discovered that all objects on closed orbits in space travel on ellipses. This includes not only all comets and planets, including Earth, but also the Moon, and satellites in orbit around the Earth or other planets.

The Second Law

Further analyzing Brahe's data, Kepler examined the speed of the planets as they orbited the Sun on their ellipses. He discovered that, here too,



(a) (b) (c) (d) (e) (f)

FIGURE 2.34 Ellipses of different eccentricities (the pictures were made by photographing a saucer at different angles).

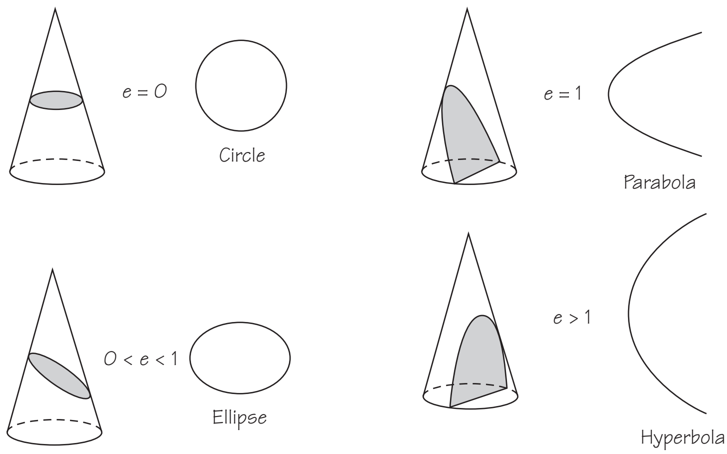


FIGURE 2.35 The conic sections, as shown in the diagram, are figures produced by cutting a cone with a plane. The eccentricity of a figure is related to the angle of the cut. In addition to circles and ellipses, parabolas and hyperbolas are conic sections, with eccentricities greater than ellipses. Newton eventually showed that all of these shapes are possible paths for a body moving under the gravitational attraction of the Sun.

Plato's assumption about planetary motions and centuries of tradition had to be given up. The planets do not travel at uniform speed, but at changing speeds in accordance with a new law, the law of areas:

> Kepler's second law of planetary motion, the Law of Areas: *An imaginary line from the sun to the moving planet sweeps out equal areas in equal amounts of time*.

To see what this means, refer to Figure 2.36. Both of the shaded parts cover equal areas, and the times for a planet to move between the two points on the orbit (AB and CD) are equal. For example, suppose it takes a planet 1 month to travel from point A to point B on the right side of the orbit, when it is nearest the Sun. It also takes the planet 1 month to travel from point C to point D on the other side of the orbit, when it is farthest from the sun. Since the times are equal in each case, this law says that the areas swept out will also be equal to each other. The only way to have both the times and the areas equal to each other is if the distances between these pairs of points are different in each case. As if moving along a giant elliptical pizza pie, the planet sweeps out a short and fat slice of area when nearest the Sun, and a long, thin slice of area when farthest from the Sun. The

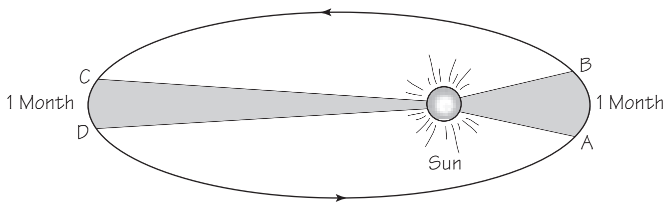


FIGURE 2.36 Kepler's law of areas. A planet (shown here with exaggerated eccentricity) moves along its orbit at such a rate that the line from the Sun to the planet sweeps over areas which are equal for equal time intervals. The time taken to cover *AB* is the same as that for *CD*.

amount of "crust," orbital distance, in each case is different—but the time of travel is the same. As you know, speed is equal to the distance over the time taken. So a larger distance of travel involves a faster speed, while a shorter distance of travel in the same time involves a slower speed. The net result? In moving from A to B near the Sun, the planet moves the fastest. In moving from C to D farthest from the Sun, the planet moves the slowest. And in between, it constantly changes speed as an imaginary line from the Sun to the planet sweeps out equal areas in equal times.

We can now see better why the seasons on Earth differ a little in length. It is not because the Sun is speeding up and slowing down as it orbits the Earth, but because it is the Earth that is doing so as it orbits the Sun on its ellipse. At the same time, the motion of the planets on ellipses with changing speeds put an end to over 2000 years of Plato's problem. In the end, there simply was no problem, because there are no perfect circles and no uniform speeds in the heavens!

Although these Kepler's laws of planetary motion had destroyed Plato's problem, Plato would probably not be too upset, because they provided a much simpler mathematical account of the observed motions of the planets than even Copernicus had provided. With just the simple ellipse and the variable speeds of the planets according to the law of areas, Kepler could do everything that Ptolemy and Copernicus could do. Yet Kepler still sought another harmony that would answer his old question why the planets move as they do in the orbits in which they are found.

The Third Law

Further years of analysis finally led Kepler to his third law of planetary motion, known as the harmonic law. This law did not give the reason "why," but it did reveal a new quantitative relationship between the periods of the planets—the period being the time it takes to complete one orbit—and their average distances from the Sun. (He could use the average distance, since all of the orbits are nearly circular.) It also tied together all of the planets, including the Earth, despite their different ellipses. Kepler's third law is an arithmetic law, not a geometric law:

> Kepler's third law of planetary motion, the harmonic law: *The squares of the periods of the planets are proportional to the cubes of their average distances from the Sun, for all of the planets.*

If we call the period of a planet T, and its average distance from the Sun R_{av}, this law can be expressed in symbols in several different, but equivalent ways, as follows:

$$T^2 \propto R_{av}^3,$$

or

$$T^2 = kR_{av}^3,$$

or

$$\frac{T^2}{R_{av}^3} = k.$$

Here k is a constant, the same constant for all of the planets. This law applies to all the planets as well as to all comets, asteroids, and any other bodies in a closed orbit around the Sun. It also applies to objects orbiting the Earth or any other planet, but in those cases there is a different value for k for each planet.

Let's see what k would be for the planets orbiting the Sun. Of course, the value of k depends upon the units chosen for T and R_{av}. Following standard practice since the days of Copernicus and Kepler, we'll use the Earth's average radius and period as our unit of measure. For the Earth, the period is 1 yr and the average radius is defined as 1 astronomical unit, or 1 AU. So, we can find the value of k in these units by substituting into the expression above:

$$\frac{T^2}{R_{av}^3} = k,$$

$$\frac{(1\text{ yr})^2}{(1\text{ AU})^3} = k.$$

Using this value of k and all periods and radii in these units, all of the other planets should have this same ratio. Let's see if we can confirm this, using the data in the table of periods and radii obtain by Copernicus, Section 2.6. For example, for Saturn, $T = 29.46$ yr, $R_{av} = 9.54$ AU:

$$\frac{T^2}{R_{av}^3} = \frac{(29.46 \text{ yr})^2}{(9.54 \text{ AU})^3} = \frac{867.9 \text{ yr}^2}{868.3 \text{ AU}^3} = 0.999 \text{ yr}^2/\text{AU}^3.$$

For Mercury, $T = 87.97$ d $= 0.24$ yr, $R_{av} = 0.39$ AU:

$$\frac{T^2}{R_{av}^3} = \frac{(0.24 \text{ yr})^2}{(0.39 \text{ AU})^3} = \frac{0.058 \text{ yr}^2}{0.059 \text{ AU}^3} = 0.983 \text{ yr}^2/\text{AU}^3.$$

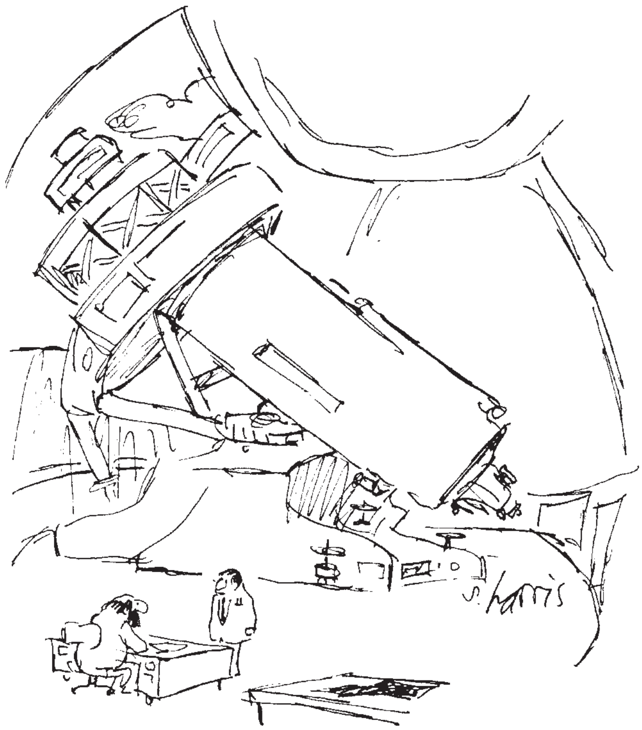
So within the limit of uncertainty, k for Saturn and Mercury are equal. Hence, if you know the average radius of a planet, you can find its period, and vice versa.

Evaluating Kepler's Work

Kepler's system was vastly simpler and more precise than the multitude of geometrical devices in the planetary theories of Ptolemy, Copernicus, and even Brahe. Kepler's three laws are so simple that their great power may be overlooked. Combined with his discovery that each planet moves in a plane passing through the Sun, their value is greater still. It is almost as if the solar system is like a gigantic mechanical machine, perhaps a clock, ticking away in precise, predictable fashion according to Kepler's laws of planetary motion. Kepler was among the first astronomers to suggest such a simile. In fact, he was the first to call this a "clockwork universe," a universe, he thought, wound up by God in the beginning and allowed to run like a mechanical clock according to a few laws of motion until the end of time. This was a powerful image, and one which we will encounter again and again.

Although Kepler believed that a magnetic "force" emanating from the Sun was the underlying origin of his laws of planetary motion, these laws are grounded in his painstaking analysis of the data. Data that are obtained from experimental research are often called empirical data, and laws obtained from such data are often called *empirical laws.* They are an important step toward obtaining a theory, but usually they cannot form a theory themselves, since we want a theory to do much more. We want an explanation why these laws occur in the data as they do.

Kepler did try to provide such an explanation by speculating about the action of the supposed magnetic force emanating from the Sun. In doing



"It's always the same thing — the sun, a few clouds, and that's it. I'd like a transfer to the night shift."

FIGURE 2.37

this he was the first mathematical astronomer to go beyond an analysis of the observations in an attempt to create a *physics* of the planetary motions—obtaining not just a mathematical description of the motions but the *cause* of the motions. In fact, the full title of his book reporting his work and discoveries was *New Astronomy*: *A Celestial Physics*.

In obtaining his second law of planetary motion, Kepler realized that the planets move fastest when they are closest to the Sun and slowest when farthest away. He reasoned from this that there might be a force from the Sun that causes the planets to speed up as they move closer. Kepler thought that this force might be a magnetic force of attraction, since recent discoveries had shown that the Earth is a large magnet, and that the strength of a magnet's effect increases as the distance to it decreases. Perhaps the Sun exerts a magnetic attraction on the Earth and other planets as they revolve around the Sun, speeding them up as they approach.

Kepler was almost right! There is an attractive force between the Sun and the planets that does account for his laws. In one of the most important theories ever developed, Newton showed that the attractive force is not magnetism but another force, the force of gravitation between all matter, whether on the Earth, in the solar system, or across the Universe (further discussed in Chapter 4). But Kepler was not able to carry his prescient idea beyond the qualitative stage.

As you will see in Chapter 4, when Newton obtained his theory of universal gravitation, he used Kepler's empirical laws as a guide. His derivation of these laws from the new theory helped to confirm the theory. The power of empirical laws such as Kepler's is in their ability to help guide to general theories from which these laws can be derived. Only then do we believe we have an understanding of the physical processes that give rise to these empirical laws. One may say empirical laws tell us "how"; theories tell us "why."

2.11 NEW OBSERVATIONS

One of the scientists with whom Kepler corresponded was his Italian colleague Galileo. Like Kepler, Galileo was opposed by scholars who believed that the heavens were eternal and could not change. Galileo therefore took special interest in the sudden appearance in 1604 of a new star, a nova. Where there had been nothing visible in the sky, there was now a brilliant star that gradually faded away. Like Brahe and Kepler, Galileo realized that such events conflicted with the then current idea that the stars could not change. Similar to the experiences of Brahe and many future scientists at a young age, this nova awakened in Galileo an interest in astronomy that lasted his entire life.

Four or five years later, as Galileo tells it, he learned that a Dutch lens maker "had constructed a spy glass by means of which visible objects, though very distant from the eye of the observer, were distinctly seen as if nearby." Galileo worked out some of the optical principles involved. Having established a scientific instrument shop in order to supplement his meager income as a professor, he set to work to grind the lenses and to build such an instrument himself. While others used the telescope primarily as a military instrument, for sighting enemy ships and invading armies, Galileo was the first to turn the instrument to the heavens. What he saw there astonished him and the public to whom he reported his observations, as it will amaze you if you have the opportunity to observe the night sky through a telescope.

FIGURE 2.38 Two of Galileo's telescopes.

Imagine being the first person ever to look at the stars through a telescope! For thousands of years people could learn about the heavens only from what they could see with their own eyes, and then only if they had good eyesight. Suddenly a whole new world opened to human eyes for exploration and study. Within a few short weeks in 1609 and 1610 Galileo used his telescope to make a series of major discoveries. First, he pointed his telescope at the Moon. Here is what he saw:

> . . . the surface of the Moon is not smooth, uniform, and precisely spherical as a great number of philosophers believe it (and other heavenly bodies) to be, but is uneven, rough, and full of cavities and prominences, being not unlike the face of the Earth, relieved by chains of mountains and deep valleys.

He did not stop with that simple observation; he supported his conclusions with several kinds of evidence, including ingenious measurements of the heights of the lunar mountains.

Next Galileo looked at the stars. To the naked eye about 3000 stars are visible in the night sky (if you are away from city lights), while the Milky

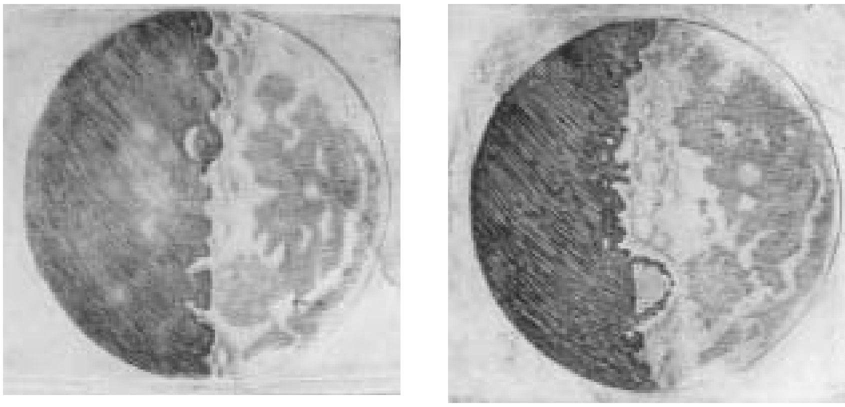


FIGURE 2.39 Two of Galileo's early drawings of the Moon from *Siderius Nuncius (The Starry Messenger)*.

Way (now understood to be the major part of our galaxy) seems to be a continuous blotchy band of faint light, almost directly overhead and to either side. Wherever he pointed the telescope, Galileo saw many more stars than had ever been seen before, and he observed the Milky Way to consist of thousands of faint stars. Today, with powerful telescopes such as the Hubble Space Telescope, astronomers can see many billions of stars and other objects—and there is as yet no end in sight.

By projecting an image of the Sun on a screen in order to protect his eyes (never look directly at the Sun!), Galileo observed dark spots on the Sun. These seemed to indicate that the Sun, like the Moon, was not perfect in the Aristotelian sense. He also noticed that the sunspots moved

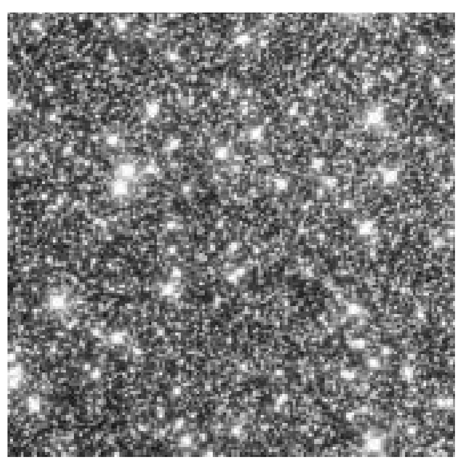


FIGURE 2.40 Image of stars from Hubble Space Telescope.

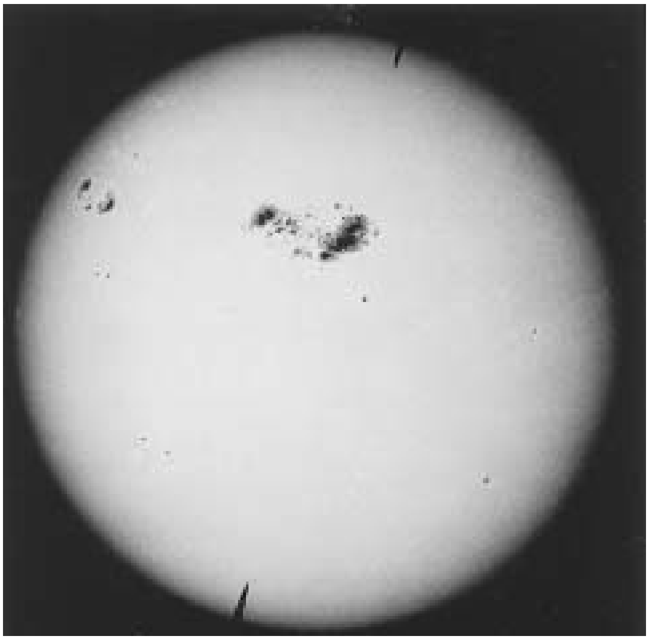


FIGURE 2.41 Solar disk with sunspots.

across the face of the Sun in a regular pattern. He concluded from further study that this motion indicated that the Sun itself rotated on its axis with a period of about 27 days. If the Sun can rotate, he asked, why can't the Earth?

Writing in Italian for the general educated public, Galileo reported on these and his many other discoveries over the following years. Among the most important was, in his words, "the disclosure of four *Planets* never seen from the creation of the world up to our time." He was referring to his discovery of four of the moons that orbit Jupiter. Here, before his eyes, was a miniature solar system, with its own center of revolution—a model for the entire solar system. He named these moons the Medician Planets, in honor of his benefactor in Florence, Cosimo dé Medici. Centuries later, in the 1990s, the first satellite sent to Jupiter for long-term study of the planet and its moons was named *Galileo* in honor of the moons' discoverer.

Galileo also observed that Saturn seemed to carry mysterious "bulges" or "ears" around its equator. The magnification of his telescopes was not large enough to show that these were really the rings of Saturn. In photographing the rings of Saturn during space missions centuries later, the *Voyager* spacecraft revealed these rings to be among the most beautiful objects in the solar system. Yet in some ways—for instance, their fine structure and delicately preserved equilibrium—they still remain mysterious.

So far, none of Galileo's observations was a clear contradiction of the Ptolemaic theory, although they did raise serious doubts. The greatest threat came with Galileo's discovery of the phases of Venus, which are also visible only through a telescope. Like the Moon, Venus shows all phases, and they are of different sizes depending upon the phase, full phase occurring with the smallest size, as shown in Figure 2.45. Galileo pointed out that the full phase should not be observed if Ptolemy's theory is valid, because in it Venus moves always between the Earth and the Sun. But Copernicus's theory can account for all of these phases, and also the different sizes, as indicated in Figure 2.46. This, he told his audience, was clear proof that Ptolemy was wrong and Copernicus was right. But in his eagerness to convince the public, he failed to mention that Brahe's "compromise theory" (see Section 2.9) also accounted for the observations of Venus, and this was still a geocentric theory (although a lopsided one), since the Earth was stationary at the center and all celestial objects orbited about it.

Having collected an impressive array of new information about the heavens with his telescopes, Galileo used it to maximum advantage. He had become convinced of Copernicus's heliocentric system earlier in his career because, like Copernicus, he found it simpler and more pleasing. Now he had observations as well as conviction. A masterful writer and debater, Galileo portrayed his observations to his Italian audience in his *Dialogue Concerning Two Chief World Systems* (1632) and earlier writings as providing irrefutable evidence in favor of Copernicus and against Ptolemy. In fact, while they certainly caused problems for Aristotle's cosmology, they were

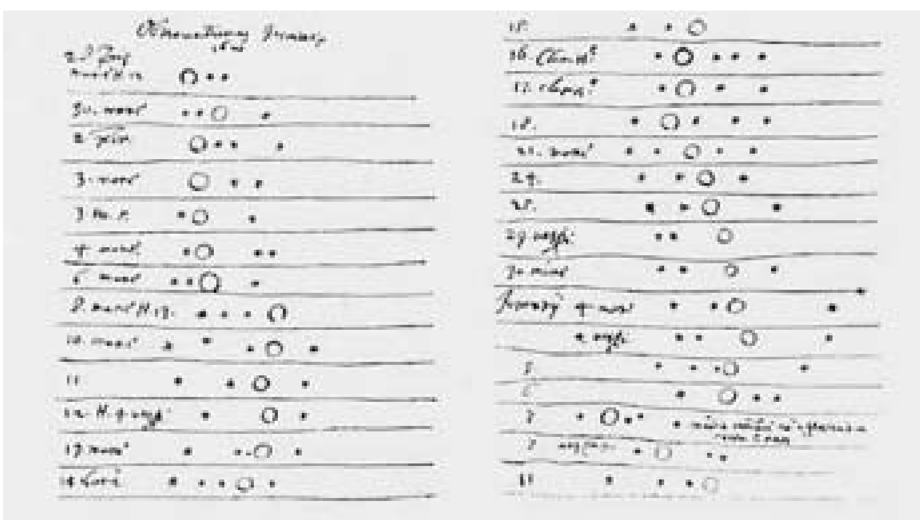


FIGURE 2.42 Galileo's drawings of Jupiter (the large circle) and its moons (the dots) on different days (from *The Starry Messenger*).

FIGURE 2.43 Palomar Observatory, located on Palomar Mountain in southern California, houses the 200-inch Hale reflecting telescope.

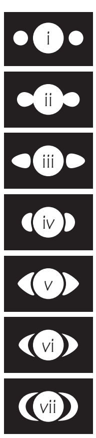


FIGURE 2.44 Saturn seen at different times, as it would have appeared to observers in the seventeenth century (reproduction of sketches).

FIGURE 2.45 Photographs of Venus at various phases with a constant magnification.

not "proof" but rather, at best, circumstantial evidence against the systems of Ptolemy and Aristotle and for Copernicus's heliocentric system. They could lead us to doubting Ptolemy and Aristotle, but not necessarily to rejecting their theories entirely. Only the phases of Venus provided a clear challenge to Ptolemy's theory—but not to all geocentric theories, since Brahe's geocentric theory could still account for the observed phases.

Apparently Galileo expected that his discoveries with the telescope would immediately demolish the deep-seated assumptions and beliefs that prevented widespread acceptance of the Copernican theory. But no matter

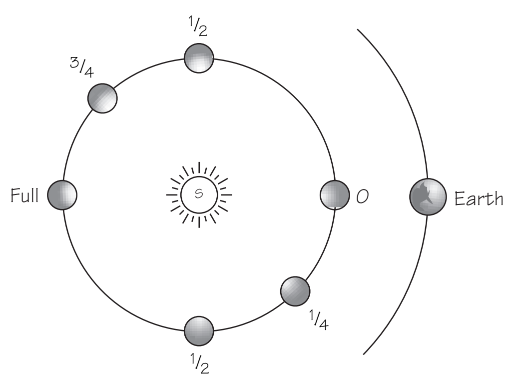


FIGURE 2.46 Explanation of phases of Venus as seen from Earth, based on the heliocentric theory.

what the evidence, people often cannot believe what they are not ready to believe. The Aristotelians firmly continued to believe that the heliocentric theory was absolutely false and contrary to direct, naked-eye observation, common sense, and religious belief. Lest Galileo gain influence among the general public and threaten cherished, pious beliefs, the religious authorities decided to forbid his teachings on this matter.

2.12 GALILEO CONDEMNED

The political and personal tragedy that struck Galileo is described in many books. Many of the documents pertaining to this case have been recently released by the Vatican and are available in English translation. We know that the period was one of turmoil for the Roman Catholic Church. In the wake of the Protestant Reformation, the Church was in the midst of its own reassessment, called the Counter Reformation, to win back some of its members. In addition, there were many intrigues occurring among various factions within the Church. These factions saw Galileo's vulnerability as an opportunity to enhance their own prestige and power within the Church hierarchy.

For several centuries the Church had supported the Inquisition, a theological court established to investigate and stamp out heresy by every means. In 1616, the same year in which the Inquisition placed Copernicus's book on the *Index of Forbidden Books*, the Inquisitors, mindful of Galileo's recent publication of some of his discoveries with the telescope, warned Galileo to cease teaching the Copernican theory as truth. He could continue to teach it only as just one of several possible hypotheses or methods for computing the planetary motions, but not as a literally true model of the Universe. Although a devoutly religious man, Galileo deliberately ruled out questions of religious faith from scientific discussions. This was a fundamental break with the past. But he was ordered "henceforth not to hold, teach, or defend it in any way whatever, either orally or in writing."

In 1632, having obtained permission of the Church censors, Galileo published his *Dialogue Concerning Two Chief World Systems*. Galileo's enemies in the Church flew into a rage when they found their views represented in the book by a fictitious Aristotelian named Simplicio, who in the end was portrayed as persuaded of the heliocentric theory. Galileo's long-time enemies, incensed by his lack of tact, argued that he had directly violated the warning of 1616. These and related motivations marked Galileo for punishment.

Among the many factors in this complex story it is important to remember that Galileo was always religiously faithful, as were most of the scientists of that era. In earlier letters Galileo wrote that God's mind contains all the natural laws. Consequently, the occasional glimpses of these laws that scientists might gain are direct revelations about God, just as true in their way as those in the Bible. He believed scientific research could be considered the retracing of God's thoughts as He created nature long ago. Today, similarly, some view science as one way to contemplate God's creation, whether they are scientists or not. Few people think of scientific findings about the world as conflicting with religion. In Galileo's time, however, such ideas were regarded as symptoms of pantheism, the belief that God is no more (nor less) than the forces and laws of nature. Pantheism was one of the religious "crimes," or heresies, for which the Dominican monk Giordano Bruno, who proclaimed the existence of other worlds, had been burned at the stake in 1600. The Inquisition, alarmed by Galileo's seeming denial of the Bible as the only literal source of knowledge about Nature and of God, ordered him to Rome to stand trial for heresy.

Although old and in ill-health, Galileo was confined in Rome, interrogated, threatened with torture, forced to make a formal confession for holding and teaching forbidden ideas, and finally forced to deny the Copernican theory as heresy. In return for his confession and denial, Galileo was sentenced only to house arrest for the remainder of his life. He never wrote again on the Copernican theory, but he managed to produce perhaps his


DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
MASSIMI SISTEMI DEL MONDO
CON PRI VILEGI.

FIGURE 2.47 Title page from Galileo's *Dialogue on Two Chief World Systems* (1632).

best work, *Dialogue Concerning Two New Sciences*, in which he presented his findings on the science of motion and mechanics. In the end, ironically, this new work—by leading to Newton's work—eventually demolished Aristotle's cosmology more thoroughly than could any polemical writings or dialogues debating the merits of different models for the solar system.

The Inquisition also placed Galileo's *Dialogue on Two Chief World Systems* on the *Index of Forbidden Books*. It remained there, along with Copernicus's book and one by Kepler, until 1835—a warning to all that demands for spiritual conformity also required intellectual conformity. The result was the noticeable decline of science in Italy for nearly two centuries. But science cannot be extinguished. Less than 50 years after the condemnation of Galileo, Newton published his great work, the *Principia*, an achievement that would not have been possible without the work of Galileo and Kepler.

In 1979, during the worldwide celebration of the 100th birthday of Albert Einstein, Pope John Paul II announced that the Vatican would reopen the case against Galileo. In 1984 it released the documents pertaining to the case, and in 1992 a papal commission acknowledged the Vatican's error in condemning Galileo for heresy.

SOME NEW IDEAS AND CONCEPTS

altitude
azimuth
celestial sphere
eastward drift
empirical laws
epicycle-deferent
equinox
geocentric theory
heliocentric theory
law of nature
nova
Renaissance
retrograde motion
Scientific Revolution
solstice
stellar parallax
Zodiac

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STUDY GUIDE QUESTIONS

1. This chapter concerns the development, debates, and impact regarding an important new scientific theory. Describe the new theory and the old theory that it challenged.
2. What was the Scientific Revolution, and what is the importance of astronomy and mechanics to it?

2.4 The Geocentric View

1. Until about A.D. 1700 most people believed that the Earth is stationary at the center of the Universe. We now know that the Earth is rotating and the stars are more or less stationary. Why would anyone believe that the Earth is stationary?
2. Looking at a sunrise, or a sunset, is it possible to decide whether the Sun is moving and the Earth is stationary or the Earth is moving and the Sun is stationary?
3. What is relative motion?
4. As seen from the Earth, briefly describe the motions of the stars, Sun, Moon, and planets.
5. Explain the origin of the seasons in the northern hemisphere in terms of the geocentric theory. (Refer to Discovery Question 4 for further inquiry on this topic.)
6. Explain the origin of the seasons in the northern and southern hemispheres in terms of the heliocentric theory.
7. How would we know that the Earth is round if we didn't have satellites and photographs from the Moon?
8. Is the sun ever directly overhead at your latitude on the Earth? Explain.

2.5 Copernicus versus Ptolemy

1. Who was Copernicus, what did he do, and why did he do it?
2. In what ways was Copernicus's theory a sharp break with the past?
3. How did Ptolemy account for the observed motion of a planet as seen from the Earth?
4. Evaluate Ptolemy's theory, including both its positive contributions as well as its problems.
5. What did Copernicus find wrong with Ptolemy's explanation?
6. How did Copernicus account for the observed motions of the planets?

2.6 Arguments for the Heliocentric System

1. Give some of the arguments in favor of the heliocentric system.
2. What reasons did Copernicus have for proposing this theory?
3. What was the numerical harmony that Copernicus found in the table of relative radii and periods of the planets?

2.7 Arguments against the Heliocentric System

1. Why wasn't Copernicus's idea immediately accepted? After all, he was right!
2. List some of the arguments at that time against his theory.
3. What was the problem of stellar parallax? How did Copernicus respond? And how did his opponents respond to his response?

2.8 Carrying Forth the Revolution

1. At the time of Copernicus's death, how did most astronomers view Copernicus's theory?
2. Comparing the abilities of the alternative theories to account for observations, did either theory have an advantage? Explain why or why not.
3. List some of the work that was done in the century and a half after Copernicus's death, and how it strengthened the case for the new theory.

2.9 New Data

1. Why would the observations of comets and new stars (novae) beyond the Moon pose a challenge for Aristotle's system?
2. What were Brahe's contributions to the debate over a model for the planets?
3. What compromise did he offer, and what were its advantages for either side of the debate?

2.10 New Orbits

1. Who was Kepler? What was he attempting to discover?
2. What did Kepler believe to be the discovery in Question 1?
3. How does a law of nature differ from a theory?
4. State each of Kepler's three laws of planetary motion in your own words.

5. Where in its orbit does a planet move the fastest? the slowest? How does this motion account for the varying lengths of the seasons on Earth?
6. The radius of the planet Venus is given in the table in Section 2.6. Use Kepler's third law to calculate the radius of its orbit, then compare with the value given in the table. Does this support Kepler's third law?
7. How did Kepler's work affect Plato's age-old problem?
8. What are empirical laws, and why are they usually not sufficient to form a theory?
9. How did Kepler attempt to account for his laws?

2.11 New Observations

1. List and briefly describe Galileo's observations with the telescope.
2. Did any of Galileo's observations completely disprove the geocentric theory?
3. What did Galileo observe about the phases of Venus, and what did he claim they proved? Was he right? Explain.

2.12 Galileo Condemned

1. Why did the Church authorities decide to try Galileo for heresy?
2. What was Galileo's position on the relationship between science and religion?
3. What was the Church's position?
4. What was the outcome of the case, in the short term and in the long term?

DISCOVERY QUESTIONS

1. Fundamental new ideas about the world are often hard to accept. Why do you think this is so? Why don't most people gladly accept new and challenging ideas if there is evidence for them?
2. This is supposed to be a physics course, so why is this chapter about astronomy?
3. Why does this chapter have a lot of material on the geocentric model, when we now know that it's wrong?
4. Section 2.4 contained a description of the seasons during 1 year as seen from a position on the northern hemisphere of the Earth. Referring to Figure 2.12, describe what happens to the seasons during 1 year as seen by an observer:
   (a) in the southern hemisphere;
   (b) at the north pole;
   (c) at the south pole.
5. What is so important about the Scientific Revolution and Copernicus's theory?
6. The relationship between science and religion has always been a hot issue. Both deal with nature and our relationship to it, but they have different approaches. Consider what are your own ideas on this controversial issue, but

feel free to discuss without having to reveal your personal beliefs one way or the other.

7. Think of some examples of beliefs and scientific theories. What is the difference, if any, between a scientific theory and a belief? Can there be some overlap? How could a scientist like Galileo also be devoutly religious?
8. In what ways has our place in nature and the Universe become even more humble than it was in Copernicus's day?
9. Set up a debate in class over the heliocentric versus the geocentric theories of the solar system. Give specific arguments for and against each side, and decide upon a winner. Then introduce a compromise and let each side evaluate its acceptability.
10. Instead of an in-class debate, write a brief dialogue between Copernicus, Ptolemy, Galileo, and a modern person, and act it out before the class.
11. Look at the reasons Copernicus gave for his new theory. Do you think they were enough to convince everyone eventually? If not, what other reasons or evidence were needed?
12. Think about or look up some of the other great theories that you know about in science, and compare some of the features of their acceptance with those of the heliocentric theory.
13. Looking back over this chapter, outline the steps in the formation, debate, and acceptance of a new, fundamental theory in physical science. Use this outline later to compare with other theories you will encounter in this course.
14. Many of the astronomers of that day were also astrologers. Why do you think this was so? What are some of the fundamental assumptions in astrology and in astronomy, and how do these two differ from each other? In what ways are they similar?
15. Many of the astronomers then were also greatly concerned with revising the calendar. Look up the history of our modern calendar in an encyclopedia or other reference work and report on it to the class.
16. Do you think a second scientific revolution, with the same implications as the first one, could occur today? Make up an imaginary theory that provides a sharp break with what we understand today about some aspect of nature or the Universe. How would political leaders, religious authorities, scientists, students, the general public, react to this imaginary theory? How does the situation in the United States today compare with the conditions that helped or hindered new theories during the Renaissance?

Quantitative

1. Pluto orbits the Sun with a period of 248.4 yr. What is its average distance from the Sun?
2. A satellite is launched into circular orbit around the Sun at a distance of 3 AU. What is the period of its orbit?
3. Assuming the Earth is a perfect sphere, what would be the altitude of the Sun at solar noon on the Summer Solstice at your latitude?

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4. On the day of the Winter Solstice, the Sun's elevation at noon in the northern hemisphere is the lowest it attains throughout the year. At some northern latitudes the Sun never rises on that day. What is the highest northern latitude at which the Sun is still visible at noon on the Winter Solstice?
5. The Moon orbits the Earth at an average distance of 384,403 km with a period (as seen from the stars) of 27.3 days. With this information, find the period of a satellite launched into a circular orbit around the Earth of radius 10,000 km.