Chapter One

The Age of Myths and Speculations

And God said, Let there be light, and there was light.
—Genesis 1:3

For thousands of years men have looked up into the star-filled night sky and have wondered about the nature of the "fixed" stars as opposed to that of the five planets wandering among the constellations of the zodiac. The daily course of the sun, its brilliance and heat, and the passing of the seasons are among the central problems that have concerned every human society. Undoubtedly, the appearance of a comet or a shooting star, the passing phenomena of clouds and rain and lightning, the Milky Way, the changing phases of the moon and the eclipses—all of these must have caused quite a sense of wonder and been the source of endless discussions.

Faced with this confusing multiplicity of brute facts, beyond their physical power to control, our ancestors sought to master these unrelated phenomena symbolically by picturing the universe in terms of objects familiar to them so as to make clear the unfamiliar and the unexplained. The cosmologies that these men set up thus inevitably reflect the physical and intellectual environment in which they lived.[1]

For example, according to a Chinese myth going back to the third century A.D., the world was originally shaped like an egg, Chaos, which separated into the earth and the sky. Between these two parts was P'an-ku, a dwarf, who daily for eighteen thousand years grew three meters, his body gradually pushing apart earth and sky. Upon his death, the heavenly bodies, thunder, lightning, rain, and the various constituents of the earth's surface were derived from his body. In particular, his eyes became the sun and the moon. Though this universe was formed from a cosmic egg, its lower half, the earth, was square and lay immobile beneath the inverted round bowl of the sky, which rotated, creating constant stellar motion around the polar star. This structure was often linked to the ancient Chinese chariot—square with an umbrella canopy. The central pole, corresponding to P'an-ku's body, linked heaven and earth.

Of greater interest to the western tradition are the ancient traditions of Egypt and Mesopotamia, from which can be traced the first attempts to liberate the subject of cosmology from the use of myth. Physical cosmology arose in the Greek colonies of the eastern Mediterranean and of southern Italy during the sixth century B.C. It flourished in Athens during the next two centuries, whence it passed

[1] There is a wide literature on these earlier cosmologies. Our own preference goes to the following books: V. Ions, *The World's Mythology* (London: Hamlyn, 1974); E. C. Krupp, *Echoes of the Ancient Skies* (New York: Harper & Row, 1983). See also P. Whitfield, *The Mapping of the Heavens* (San Francisco: Pomegranate Artbooks, 1995).

on to Alexandria, which became the center of Hellenistic culture for several centuries.[2]

Unfortunately, although that golden age saw great advances in observational astronomy and mathematics, physics did not keep pace with these sciences. Thus, lacking a firm theoretical base and constrained by metaphysical dogma, physical cosmology stagnated at the dawn of the Christian era until resurrected in the Renaissance. This period, which was essentially the transition of the medieval to the modern order, saw the beginning of a great burst of critical speculation about nature and with it the emergence of two most promising ideas—the demotion of the earth from its position as the center of motion of the universe, and the existence of an infinite universe populated with an infinity of worlds. The times were not ripe for the general acceptance of these ideas, however, since it was not until late into the seventeenth century that the new science of dynamics and the law of gravitation made the age-old geocentric universe obsolete.[3]

1.1 ANCIENT EGYPT AND THE MIDDLE EAST

In the many stories recorded in texts of the third and second millennia B.C. in Egypt, Mesopotamia, and neighboring countries, the tales of creation are presented as a series of births and cosmic battles among the gods. The mother country is always represented as the center, the earth being a flat disk surrounded by a rim of mountains and floating on an ocean.

The Egyptians believed that in the beginning a primordial abysmal ocean, deified as Nun, filled the universe like a cosmic egg. Just as the Nile floodwaters receded, leaving behind fertile lands, so a primeval hill rose out of Nun. In a Heliopolitan text on papyrus from the fifth dynasty (c. 2500–2350 B.C.), Atun—a predynastic sun-god, later identified with the sun-god Ra—arose out of the abyss. He created a son, Shu—god of wind or air—and a daughter, Tefnut—goddess of lifegiving dew. Shu and Tefnut begot the twins Geb and Nut. Nut was the sky-goddess. She was sometimes pictured as an elongated woman bending over the earth-god Geb and separated from him by her father Shu (see figure 1.1). To the Egyptians, the sky was a heavenly Nile, along which the barque of the sun-god Ra sailed from east to west each day. (The sun was occasionally thrown into an eclipse when his barque was attacked by a great serpent.) Below, the earth-god Geb was lying prone in the center of a circular ocean, the Nile flowing through the fertile lands of Egypt and into the subterranean abode of the dead through which the night-barque of the sun-god Ra sailed. It was also believed that the sky-goddess Nut swallowed the sun

[2] For a detailed presentation of Greek astronomy, see T. Heath, *Aristarchus of Samos: The Ancient Copernicus* (Oxford: Clarendon Press, 1913; New York: Dover Publications, 1981); O. Neugebauer, *A History of Ancient Mathematical Astronomy*, 3 vols. (New York: Springer-Verlag, 1975). For an overall picture, see G.E.R. Lloyd, *Early Greek Science: Thales to Aristotle / Greek Science after Aristotle*, 2 vols. (London: Chatto & Windus, 1970/1973).

[3] See especially R. K. DeKosky, *Knowledge and Cosmos: Development and Decline of the Medieval Perspective* (Washington, D.C.: University Press of America, 1979); D. C. Lindberg, *The Beginnings of Western Science* (Chicago: University of Chicago Press, 1992); J. C. Pecker, *Understanding the Heavens* (New York: Springer-Verlag, 2001).

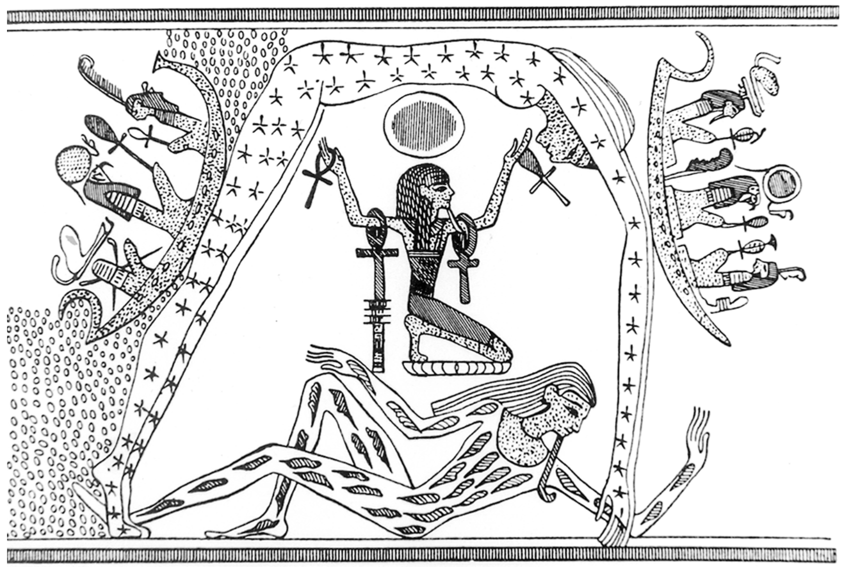

Figure 1.1 The Egyptian sun-god Ra traveling in his barque across the arc of the sky formed by the sky-goddess Nut (figure adorned with stars). She is prevented from falling upon the earth-god Geb (figure adorned with leaves) by her father Shu, the god of wind and air. From *Pioneers of Science* by O. Lodge (London: Macmillan, 1893; New York: Dover Publications, 1960).

each evening but that it was reborn from her loins each morning. Then, as the sun rose in the sky, she would swallow the stars and give birth to them again at sunset.

The theory that the shape of the universe resulted from the forceful separation of heaven from earth by a third party was also adopted in Mesopotamia.[4] It is recorded in the great Babylonian epic called, from its opening sentence, *Enuma Elish*, "When above …." The composition of its earliest known version goes back to the middle of the second millennium B.C., but we know that it had its roots in an ancient Sumerian story of about 3000 B.C. It seems that Enlil, the city-god of Nippur, was the original hero of the epic and that he was merely replaced by Marduk, the city-god of Babylon, when the later version was composed. This epic was extremely popular since, later on, an Assyrian version of the first millennium B.C. substituted the name of Ashur, the national god of the Assyrians, for that of Marduk. It is recorded on seven clay tablets.

Enuma Elish presents the earliest stage of the universe as one of watery chaos. This chaos was closely modeled on the Iraqi seashore, with large pools of sweet water mingling freely with the salty waters of the Persian Gulf, and with low banks of clouds hanging over the horizon. It consisted of Apsu (the sweetwater ocean), his wife Tiamat (the saltwater ocean), and their son Mummu (the cloud banks and mist rising from the two bodies of water). The myth of creation relates how the primordial forces of chaos bore the other gods of the Mesopotamian pantheon who,

[4]See A. Heidel, *The Babylonian Genesis*, 2nd edition (Chicago: University of Chicago Press, 1951).

in turn, created the earth and the heaven. One of these gods was Ea. To make a long story short, after overcoming Apsu and Mummu, the god Ea fathered Marduk, who possessed outstanding qualities and so was chosen by the gods to fight the remaining evil forces of chaos. After an epic combat, Marduk pierced Tiamat's heart with an arrow and smashed her skull with his mace. Then he completed creation, making half of her dead body into the sky and placing the other half beneath the earth. After his victory, Marduk put the universe in order and organized the calendar. Thus, on the sky he had fashioned he set up the constellations to determine, by their rising and setting, the years, the months, and the days. On both sides of the sky, where the sun comes out in the morning and leaves in the evening, he built gates and secured them with strong locks. Marduk also made the moon shine forth and entrusted the night to her. (It is to be regretted that the only extant clay tablet dealing with the creation and organization of the heavenly bodies breaks off at the point where it reports some detailed orders to the moon.) Then, according to the last two tablets, Marduk decided to create man and to impose upon him the service which the defeated forces of chaos had to render to the gods.

It has long been recognized that *Enuma Elish* contains several points that invite comparison with the biblical account of creation which was compiled by the Priestly school during the fifth century B.C. Indeed, *Enuma Elish* and Genesis (1:1–2:3) both refer to a watery chaos, which was separated into heaven and earth. However, in Genesis it is the Spirit of God which hovers over the waters and divides the light from the darkness; thus, as is fitting to a monotheistic religion, He alone created the heavens and the earth. Both texts also refer to the existence of light and to the alternation of day and night before the creation of the celestial luminaries. And in both texts the succession of creative acts virtually follows in the same order, culminating in the creation of mankind. At this juncture it is worth noting that the Koran, which was written during the first half of the seventh century A.D., also presents an elaborate account of creation that shows quite evident biblical traces. Thus, in sura 21:30 we learn that "the heavens and the earth used to be one entity, and then (God) parted them"; whereas in sura 71:15–16 we are told that "God created seven heavens in layers" and that "He placed the moon therein as a light and the sun as a lamp." The creation of the heavens and the earth in six days, which is mentioned in sura 7:54, also finds its counterpart in Genesis.

1.2 IONIA: THE EASTERN GREEK SCHOOL

Before the sixth century B.C. and the time of rationalism heralded by Ionian philosophers, Greek cosmologies were dependent on traditions that came from more ancient civilizations. The first records containing the early Greek ideas are due to Homer and Hesiod. Homer's two epics, the *Iliad* and *Odyssey*, are mainly devoted to the Trojan war and to the return of Ulysses in his homeland. Hesiod, the father of Greek didactic poetry, probably flourished during the eighth century B.C. His poem *Theogony* tells of the generations of the gods and attempts in mythical terms to provide an account of the events that brought the world into being. His other poem *Works and Days* resembles a modern almanac in that it correlates the agricultural work to be done with the rising or setting of certain stars. Both HOMER and HESIOD agree upon the fact that the earth is a circular disk surrounded by the river Oceanus. Over the flat earth is the vault of heaven; below the earth is Tartarus, the realm of the underworld. The vault of heaven remains forever fixed; the sun, the moon, and the stars move round under it, rising from Oceanus in the east and plunging into it again in the west. We are not told what happens to the heavenly bodies between their setting and rising. They cannot pass under the earth, however, because Tartarus is never lit up by the sun. Possibly they float round Oceanus, past the north, to the points where they rise again in the east.

The great achievement of the Ionian philosophers—Thales, Anaximander, and Anaximenes—was that of dissipating the haze of myth from the origins of the world. The three of them flourished during the sixth century B.C. in Miletus —a rich Greek city on the Aegean, near the mouth of the Maeander River. Tradition tells that Thales (c. 624–547 B.C.) was a man of great versatility: successful businessman, statesman, engineer, mathematician, and astronomer. Anaximander (c. 611–547 B.C.), who was the successor and probably pupil of Thales, was the first to have developed anything like a cosmological system; he was also the first among the Greeks who ventured to draw a map of the inhabited earth. It seems almost certain that Anaximenes (c. 585–528 B.C.), the younger contemporary of Anaximander, was the first to distinguish the planets from the "fixed" stars in respect of their irregular movements; he also extended Anaximander's ideas on cosmology.

THALES thought the earth to be a circular or cylindrical disk that floated on the cosmic ocean, like a log or a cork, and was surrounded by its waters. So far as we can judge of his views of the universe, he would appear to have regarded water as the world's fundamental element. In this conception, therefore, far above the solid earth floating on a mass of water stands the vault of heaven, which is also bounded by the primeval waters. As a matter of fact, the significance of this cosmology does not lie so much in the primacy of water as in the attempt to search for causes within nature itself rather than in supernatural events.

ANAXIMANDER offered a much more detailed picture of the world. He maintained that the earth was in the center of all things, suspended freely and without support, whereas Thales regarded it as resting on water. Anaximander's earth had the shape of a cylinder, round like a stone pillar, its height being one-third of its diameter. Still more original was his conception of the sun, moon, and stars, and of their motions. Indeed, these celestial bodies were not thought to be objects but holes in rotating hoops filled with fire.

To be specific, Anaximander's stars are compressed portions of air, in the shape of rotating hoops filled with fire, that emit visible flames from small openings, thereby producing what we see as the stars. The hoops belonging to the sun, the moon, and the stars were probably assumed to be concentric with the earth. The sun is thus a rotating hoop full of fire, which lets its fire shine out through an opening like the tube of a blowpipe. The moon sometimes appears as waxing, sometimes as waning, to an extent corresponding to the opening or closing of the passages in its hoop. The eclipses of the sun and the moon occur when the openings in their hoops are shut up. For some philosophical reason, however, the radius of the solar hoop is twenty-seven times as large as the earth, whereas that of the lunar hoop is eighteen times as large as the earth. Surprisingly, the hoops from which the stars and planets shine are *nearer* to the earth than that of the moon. Despite some obvious shortcomings, this cosmological system represents a definite improvement over previous ones since, instead of moving laterally round the earth, the heavenly bodies describe circles passing *under* the earth, which is freely suspended in space.

For ANAXIMENES the earth is still flat but, instead of resting on nothing, it is supported by air. The sun, the moon, and the planets are all made of fire, and they ride on the air because of their breadth. The sun derives its heat from its rapid motion, whereas the stars, which are also composed of fire, fail to give warmth because they are too far off. It is also assumed that the stars are fastened on a crystal sphere, like nails or studs. Obviously, a definite improvement on Anaximander's system is the relegation of the stars to a more distant region than that in which the sun moves. And, as we know, the rigidity of the sphere of the fixed stars remained the fundamental postulate of all astronomy up to the beginning of modern science.

Highly speculative theories about the nature of the heavenly bodies were also proposed by Xenophanes (c. 570–478 B.C.) of Colophon and Heraclitus (c. 540–480 B.C.) of Ephesus. XENOPHANES was more a poet and satirist than a natural philosopher. According to him, the stars (including the comets and shooting stars) are made of clouds set on fire; they are extinguished each day and are kindled at night like coals, and these happenings constitute their setting and rising, respectively. The sun and the moon are also made of clouds set on fire. On the contrary, HERACLITUS assumes that the stars are bowls turned with their concave sides toward us, which collect bright exhalations arising from the earth and from the sea, thus producing flames. The sun and the moon are also bowl shaped, like the stars, and are thus similarly lit up.

1.3 SOUTHERN ITALY: THE WESTERN GREEK SCHOOL

Much more remarkable developments were to follow in the great colonies of southern Italy. The dominant figure is undoubtedly Pythagoras, who gave his name to an order of scientific and religious thinkers. He was an Ionian, born at Samos about 572 B.C. The important part of his career began about the year 530 B.C. with his migration to Crotona, a Dorian colony in southern Italy. Political reaction against his brotherhood brought about his retirement to Metapontum, on the Gulf of Taranto, where he died at the turn of the fifth century B.C.

PARMENIDES of Elea, who was a contemporary of Heraclitus, is said to have been the first to assert that the earth is spherical in shape and lies in the center of the universe. There is, however, an alternative tradition stating that it was PYTHAGORAS who first held that the universe, the earth, and the other heavenly bodies are spherical in shape, that the earth is at rest at the center, and that the sphere of the fixed stars has a daily rotation from east to west about an axis passing through the center of the earth. Pythagoras and his immediate successors left no written exposition of their doctrines. Thus, although it is most likely that Pythagoras arrived at geocentrism and the rotundity of the earth from mathematical considerations, Parmenides—who was closely connected with the Pythagoreans—may have been the first to state the doctrine publicly.

It is improbable, however, that Pythagoras himself was responsible for the astronomical system known as Pythagorean, which reduces the earth to the status of a planet like the others. This cosmology is often attributed to PHILOLAUS of Crotona, who flourished in the latter half of the fifth century B.C.

The Pythagorean system may be described briefly as follows. The universe is spherical in shape and finite in size. At its center is the central fire, in which is located the governing principle—the force that moves the celestial bodies, including the earth, on their circular paths. The outer boundary of the sphere is an envelope of fire, which is called Olympus; below this is the universe. In the universe there revolve in circles round the central fire the following bodies. Nearest to the central fire revolves a body called the counterearth, which always accompanies the earth, the earth's orbit coming next to that of the counterearth; next to the earth, reckoning in order from the central fire outward, come the moon, the sun, the five planets, and last of all, outside the orbits of the planets, the sphere of the fixed stars.

Philolaus explained that the Greeks had never seen the central fire nor the counterearth because the earth turned so as always to place their country away from those objects. Such a situation implies that the earth is rotating around its axis in the same time as it takes the earth to complete a revolution around the central fire. Obviously, this was a giant step forward since it provided a simple explanation for the apparent daily motion of all celestial objects. What evidence motivated Philolaus to include a counterearth is not clear, however, but it could have been invented for the purpose of explaining the frequency of eclipses of the moon. Arguably, it could have been added to bring the number of celestial objects up to ten, the perfect number according to the Pythagoreans.

It is worth noting that the sun is not a body with light of its own in this cosmological model. Instead, the sun is made of a substance comparable to *glass* that concentrates rays of fire from elsewhere and transmits them to us. It is not stated, however, whether these rays of fire come from Olympus or from the central fire. A similar conception for the nature of the sun has been attributed also to EMPEDOCLES (c. 490–430 B.C.) of Acragas in Sicily. More importantly, Empedocles advocated the idea that there are four primary substances—fire, air, water, and earth—out of which all the structures in the world are made by their combination in different proportions.

1.4 THE ATHENIAN PERIOD

During the first half of the fifth century B.C., both the Ionian and the Italian schools of natural philosophy were progressively overshadowed by Athens, which became for two centuries the intellectual center of the Greek world. The Ionian ANAXAGORAS seems to have been the first natural philosopher to move to Athens. He was born in Clazomenae, near modern Izmir, about 500 B.C. He came to Athens about the year 464 B.C., where he enjoyed the friendship of the statesman Pericles (490–429 B.C.). However, when Pericles became unpopular during the late 430s B.C., shortly before the outbreak of the Peloponnesian war, he was attacked through his friends; and so

Anaxagoras was prosecuted on a charge of impiety for holding that the sun is a red-hot mass and the moon like earth. According to one account of the events, Pericles managed to save him, but Anaxagoras was forced to leave Athens. Eventually, he withdrew to Lampsacus in Asia Minor, near modern Gallipoli, where he died about 428 B.C. This is an early case of persecution of scientific ideas opposed to current views.

His greatest achievement was the discovery of the fact that the moon does not shine by its own light but is illuminated by the sun. As a result, he was able to give the correct explanation of eclipses. He thus held that the eclipses of the moon were caused by its falling within the shadow of the earth, which then comes between the sun and the moon, while the eclipses of the sun were due to the interposition of the moon. Whether he reached the true explanation of the phases of the moon is much more doubtful, however.

Anaxagoras also developed a cosmological system according to which the formation of the world began as a huge vortex set up by a *deus ex machina* in the primordial chaos. From the violence of this whirling motion, which is still visible on the sky, he was able to explain the formation of the earth and, thence, of the heavenly bodies. In his view, therefore, the initial vortex caused the heavy earth to collect at the center of the world while the surrounding ether tore stones away from the earth and kindled them into planets and stars revolving around us. Obviously, this is an indefinitely expanding universe since there is no spatial limit set to the expansion of the ripples from the initial vortex. Parenthetically note that another cosmogony initiated by a vortex was suggested by his contemporary LEUCIPPUS of Miletus, with an infinity of *atoms* taking the place of Anaxagoras' initial mixed mass in which "all things were together." There is also the difference that material and space are supposed to be limitless so that there would be an unlimited number of worlds similar to our own world-system in the universe.

Apart from these remarkable innovations, Anaxagoras did not improve much upon the earlier Ionian theories. Following Anaximenes, he thus assumed that the earth was flat and supported by air; and that the sun, the moon, and all the stars were stones on fire. However, he also held the view that the moon was of earthy nature and had in it plains, mountains, and ravines. According to Anaxagoras, the sun was "rather larger than the Peloponnese."

At this juncture it is worth noting that Anaxagoras also put forward a very original hypothesis to explain the Milky Way. As we have seen, he thought the sun to be *smaller* than the earth. Hence, when the sun in its revolution passes under the earth during the night, the shadow cast by the earth extends without limit. Since the stars within this shadow are not illuminated by the sun, it follows that we can see them shining; those stars, on the other hand, that are outside this shadow are overpowered by the rays of the sun, which shines on them even during the night, so that we cannot see them. According to Anaxagoras, the Milky Way is the reflection of the light of those stars that the sun cannot see when it is passing below the earth. Although this conjecture can be easily disproved by observation, it was supported by DEMOCRITUS (c. 460–370 B.C.) of Abdera. As far as we know, Democritus seems to have been the first to appreciate the true character of the Milky Way as a multitude of faint stars so close together that it has the appearance of a continuous body of light.

Important for subsequent astronomical developments were the Athenian Plato (c. 427–347 B.C.) and his pupil Aristotle (384–322 B.C.), who was born at Stagira, a Greek colonial town on the Aegean near modern Salonika. Although Plato is primarily known as a philosophical writer, he himself probably felt that the foundation of the Academy in about 387 B.C. was his chief work. Aristotle entered the Academy in about 367 B.C. and worked there for twenty years by the side of Plato. After acting for some years as tutor to the young Alexander (356–323 B.C.) in Macedonia, he returned to Athens to found his own institute of higher education, the Lyceum, which came to be known as the Peripatetic School from the path in his garden where he walked and talked with his pupils.

The importance of PLATO, so far as the development of astronomy is concerned, is to be sought in his appreciation of the role of mathematics in making intelligible the motions of the heavenly bodies. Tradition tells that the motto "Let none who has not learned geometry enter here" was inscribed over the entrance of the Academy. Following in this the Pythagoreans, the apparently irregular motions of the planets had, in his opinion, to be accounted for in terms of combinations of uniform circular motions only. This was to become the main task of astronomers from his time to the dawn of the seventeenth century—a stretch of two thousand years.

EUDOXUS (c. 408–355 B.C.) of Cnidus, who came to Athens at the age of twenty-three where he heard Plato and the sophists, is one of the key figures in the history of Greek astronomy. His most influential contribution was his cosmological model based on concentric spheres centered on the earth, which is itself a sphere at rest. Thus, each heavenly body is attached to the surface of an imaginary invisible sphere which is rotating uniformly around a fixed direction. Each sphere is itself attached to a larger sphere rotating around another axis. The secondary spheres could be succeeded, in turn, by a set of interlocking spheres according to the observed positions of each heavenly body. In this representation, twenty-seven spheres in all were considered sufficient: three each for the sun and moon, four for each of the five planets, and one for the fixed stars. Further improvements were made by CALLIPPUS (c. 370–300 B.C.) of Cyzicus, who added further imaginary spheres to the model, making use of thirty-four concentric spheres in all.

Of great interest also is the work of ARISTOTLE, since his picture of the universe was to become the orthodox view of cosmology in the universities of western Europe from the thirteenth to the seventeenth century (see figure 1.2). In his astronomy, Aristotle builds upon the mathematical results of Eudoxus and Callippus in their use of concentric spheres centered on the earth. However, what were for these astronomers mere mathematical devices of representation are regarded by him as physical entities. The heavenly bodies must also be thought of as composed of a distinctive ethereal substance, different from the objects found below the sphere of the moon. The latter alone are made of varying combinations of earth, water, air, and fire. Beyond the moon's orbit, both the visible heavenly bodies and their invisible spheres are therefore composed of a fifth element, a special *ether*, the movement of which is always circular. Finally, beyond all these spheres is the outermost heaven, the *primum movens*, that communicates its motion to the whole system. Aristotle's world is of finite extent and has neither beginning nor end.

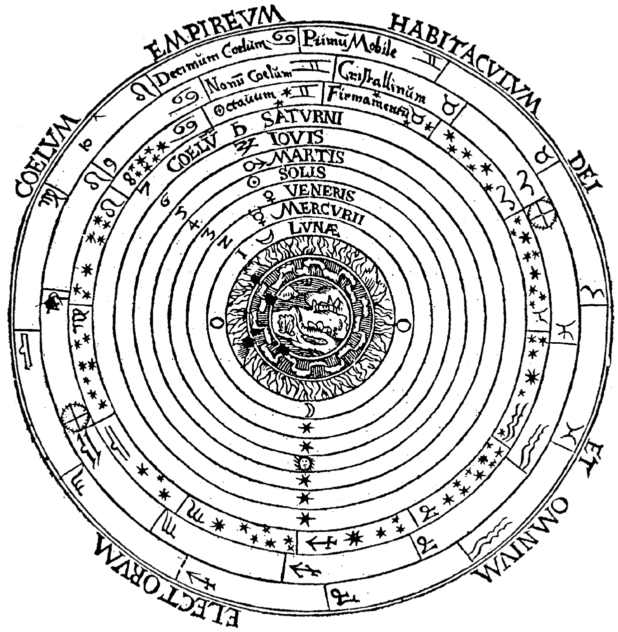

Figure 1.2 The cosmic system of Aristotle as presented by Petrus Apianus around 1530. This geocentric universe focuses on a round earth articulated into four concentric spheres, one for each of the four elements. Surrounding these spheres are seven planetary spheres, one for each of the seven planets. The "eighth heaven" is the sphere of the fixed stars. The "ninth heaven" is a transparent, crystalline sphere that nonetheless reflects the signs of the zodiac. The "tenth heaven," which is the *primum movens* that communicates its motion to the whole system, is the boundary of the universe, and beyond it lies the habitation of God and all the Saints. The addition of this infinite, God-filled void space was an essentially Christian reaction to Aristotle's claim that there can be "neither place, nor void, nor time beyond the sphere of the fixed stars." From S. K. Heninger, Jr., *The Cosmographical Glass: Renaissance Diagrams of the Universe* (San Marino, Calif.: Huntington Library, 1977). By permission of the Huntington Library.

If so, then, by what mechanism do the sun, stars, and planets shine? This problem is also discussed in Aristotle's treatise *De caelo* (On the heavens), where it is argued that the warmth and light that proceed from the heavenly bodies are caused by *friction* set up by their motion. According to Aristotle, therefore, the heavenly bodies are not themselves fiery, as was suggested by the Ionian philosophers. Rather, they shine because they are carried on moving spheres, so that the substance underneath the sphere of each of them is necessarily heated by its motion, and particularly in that part where the body is attached to its sphere. In his treatise *Meteorologica*, Aristotle further argues that the sun's motion alone is sufficient to produce heat in the place where we live because it moves swiftly and is not so far off as the stars. In his own terms: "For a motion that is to have this effect must be rapid and near, and that of the stars is rapid but distant, while that of the moon is near but slow, whereas the sun's motion combines both conditions in a sufficient degree."

Another brilliant pupil of Plato was HERACLIDES PONTICUS (c. 388–315 B.C.) of Heraclea on the Black Sea (present-day Eregli, Turkey). His great advance in astronomy was his suggestion that the earth is in the center of the universe and rotates around an axis while the sphere of the fixed stars is at rest. This is clearly at variance with the views held by Aristotle. Heraclides has often been credited also with the claim that Venus and Mercury circle round the sun like satellites, but recent studies have revealed this interpretation of ancient texts to be without rational basis. Actually, the first clear evidence for such a hypothesis in relation to the motion of the inner planets is found in the works of THEON of Smyrna, who flourished in the early part of the second century A.D.[5]

Throughout antiquity, natural philosophers were also divided on many other aspects of Aristotelian cosmology, such as the finitude of the universe and the continuity of matter. Indeed, although the Athenian philosopher EPICURUS (341–270 B.C.) of Samos was especially celebrated for his ethical teaching, he contributed to cosmology by holding the views that the universe has no limit and that "nothing can arise out of nothing and nothing can be reduced to nothing." Following the doctrines of Leucippus and Democritus regarding the atoms and the void, he also taught that the number of these irreducible particles of matter and the extent of empty space are infinite. According to Epicurus, the universe therefore consists of numberless worlds strewn throughout an infinite void, with all matter composed of atoms and regulated by natural laws. His most eminent Roman advocate was the poet and philosopher LUCRETIUS (c. 95–55 B.C.), whose poem *De rerum natura* (On the nature of things) is the fullest statement extant of the atomist theory. However, about the same time Epicurus established his cosmology, another system of philosophy was founded by ZENO (c. 320–250 B.C.) of Citium in Cyprus, who came to Athens and set up a school in a roofed colonnade called a *stoa*. The Stoics were also ready to accept that space by its nature is edgeless; however, they argued for a rival cosmological system consisting of a finite starry universe surrounded by a void of infinite extent which is regularly drawn into it and then exhaled. The void is actually needed to provide a region in which the universe, as a living creature, continually breathes in and out in its entirety. Specifically, the Stoics regarded the physical world as a dynamical continuum, made coherent by the all-pervading *pneuma*, a mixture of air and fire, which imparts to matter its structure and all physical qualities. Through its inherent tensions the pneuma was also thought to constitute a kind of elastic medium for the propagation of physical action in the universe as a whole. The Epicurean and Stoic systems—that is, atomism and continuum theory—greatly influenced the Scientific Revolution of the seventeenth century.[6]

[5] See G. J. Toomer, *Dictionary of Scientific Biography*, **15**, 202 (1978); and especially B. S. Eastwood, *J. History Astron.*, **23**, 232 (1992).

[6] See E. Harrison, "Newton and the Infinite Universe," *Physics Today*, **39**, No. 2, 24 (1986).

1.5 THE ALEXANDRIAN PERIOD

While Aristotle was teaching in Athens, his former pupil Alexander of Macedonia was carving out a large military empire that brought Greek science into direct contact with the older sources of culture in the East. When Alexander died in 323 B.C., his empire broke down, and Egypt was seized by Ptolemy, one of his generals. Alexandria, which was founded by Alexander in 332 B.C., became the capital of Egypt during the reigns of Ptolemy and his successors. The Ptolemies were patrons of learning; they founded the Museum, temple of the Muses, which contained a large library and an observatory, and the city soon became the center of Greek scientific thought.

Among the earlier members of the Alexandrian school was ARISTARCHUS (c. 310–230 B.C.) of Samos, who was the first to put forward the heliocentric hypothesis. Although his original text is no longer extant, his most important witness is ARCHIMEDES (287–212 B.C.) of Syracuse, who made explicit mention of Aristarchus' contribution in his treatise *Arenarius*, noting that "his hypotheses are that the fixed stars and the sun remain unmoved, that the earth revolves about the sun in the circumference of a circle, the sun lying in the middle of the orbit." On this ground the Stoic philosopher CLEANTHES (c. 301–232 B.C.) declared that it was the duty of Greeks to indict Aristarchus on the charge of impiety for putting in motion the hearth of the universe.

About a century later, the heliocentric hypothesis was also rejected by the greatest of observational astronomers of antiquity, HIPPARCHUS (c. 190–120 B.C.) of Nicaea in Asia Minor. The reasons that weighed with Hipparchus were presumably the facts that a system in which the sun was the exact center did not seem to account for the variations of distance and the irregularities of planetary motion; that the theory of epicycles did apparently suffice to describe the phenomena; and that the latter could be reconciled with the commonly held view according to which the earth was immobile.

When Hipparchus came to examine suitable kinematic patterns for the planets, he had before him the techniques of the eccentric circle and epicycle. The simple device that was found satisfactory in the case of the sun was the use of an *eccentric*, that is, a circular orbit whose center does not coincide with the position of the observer on the earth. However, a more enduring solution was broached by a pure mathematician, APOLLONIUS (c. 240–170 B.C.) of Perga, who lived for some time in Alexandria. In this approach each planet moves uniformly on a small circle, called the *epicycle*, whose center moves on a larger circle, called the deferent. The epicyclic view largely prevailed through the mediation of Claudius Ptolemaeus, commonly known as PTOLEMY, who flourished in Alexandria about the middle of the second century A.D. (He was not related to the ruling dynasty of the Ptolemies.) His great treatise, later known as the *Almagest*,[7] largely refines upon the work of his predecessors, notably Hipparchus, and brings to a systematic culmination all the efforts of Greek astronomy. The *Almagest* also contains a catalog giving the ecliptical coordinates and magnitudes of 1,022 stars, based in part on the lost catalog by

[7]The Greeks called it the *megalē syntaxis*, or great composition. The Arabian translators converted *megalē*, great, into *megistē*, greatest, and hence it became known to the Arabs as *Al Magisti*, whence the medieval Latin *Almagestum* and our *Almagest*.

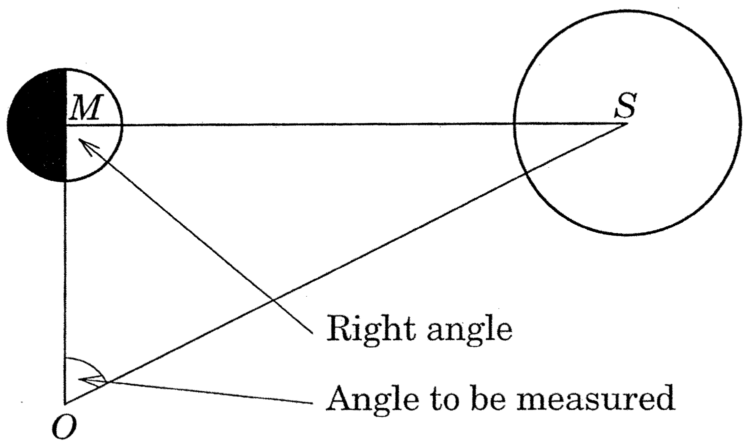

Figure 1.3 The measurement of the relative distances of sun and moon from earth (not to scale).

Hipparchus. In a later book, *Hypotheses of the Planets*, Ptolemy attempted to produce a physical system that would fulfill the requirements of both the mathematical theory expounded in the *Almagest* and his philosophy of nature.[8] The basic idea was to assume that the planets were carried around by a sequence of nested eccentric shells (of an invisible ethereal substance), within each of which the epicycles would revolve. This geocentric and epicyclic representation of the world remained virtually unchanged until the Renaissance.

Another important advance in astronomy was made when Aristarchus attempted to measure the relative distances of the sun and moon from the earth, and their sizes relative to each other. He knew that the light of the moon was reflected from the sun. Accordingly, if in figure 1.3 the points O, S, and M denote, respectively, the observer and the centers of the sun and moon, the moon appears to the observer half full when the angle OMS is a right angle. When this is the case, the observer can measure the angle MOS. With a knowledge of the angles at the points M and O, the relative lengths of the sides OS and OM can be obtained, thus giving at once the relative distances of the sun and moon from the observer.

Aristarchus made the angle MOS about 87°. Lacking the tools provided by trigonometry, he used purely geometrical reasoning to estimate that the distance to the sun was from 18 to 20 times that of the moon, whereas the correct value is about 390. Aristarchus further estimated that the apparent sizes of the sun and moon were about equal, and correctly inferred that the relative sizes of these bodies were in proportion to their distances. By a method based on eclipse observations, which was afterward developed by Hipparchus, he also found that the diameter of the moon was about one-third that of the earth, a result not far from true. Thus, in spite of large observational errors, Aristarchus was nevertheless able to show convincingly that, while the moon is smaller than the earth, the sun is much larger.

[8]See especially A. Murschel, *J. History Astron.*, **26**, 33 (1995).

To ERATOSTHENES (c. 276–194 B.C.) of Cyrene, who was librarian of the Museum at Alexandria, we owe one of the first scientific estimates of the earth's radius. He knew that at noon at the summer solstice the sun threw no shadow at Syene (near modern Aswan), while at the same hour at Alexandria the angular distance of the sun from the zenith was about 7°. Now, if in figure 1.4 the point *S* denotes the

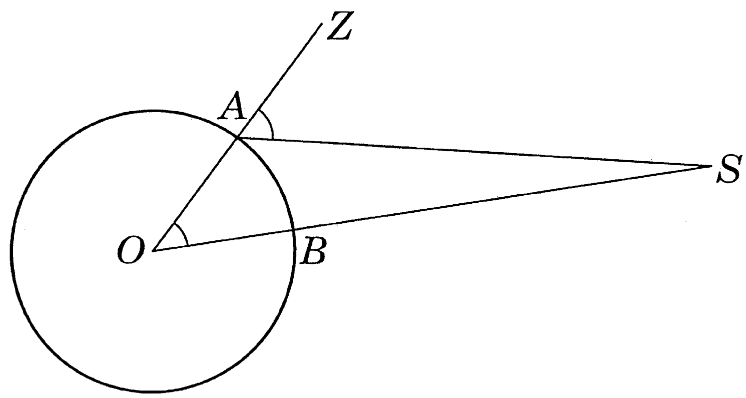

Figure 1.4 The measurement of the earth's radius.

sun, the points *A* and *B* Alexandria and Syene, respectively, the point *O* the center of the earth, and AZ the direction of the zenith, the angle SAZ is almost equal to the angle SOZ owing to the great distance of the sun, so that the arc AB is to the circumference of the earth in the proportion of 7° to 360°. The distance between Alexandria and Syene being about 5,000 stadia, Eratosthenes estimated the earth's circumference to be about 250,000 stadia. If the value of the stadium used was the common Olympic stadium, or 157.5 meters, then his evaluation of the earth's radius is about one percent in error. This good agreement with modern values is perhaps fortuitous, however, since both the angle (7°) and the distance (5,000 stadia) have obviously been rounded.

Hipparchus improved on Aristarchus' method and made a satisfactory estimate of the distance of the moon by observing the angular diameter of the earth's shadow at the distance of the moon during an eclipse. In figure 1.5, which represents

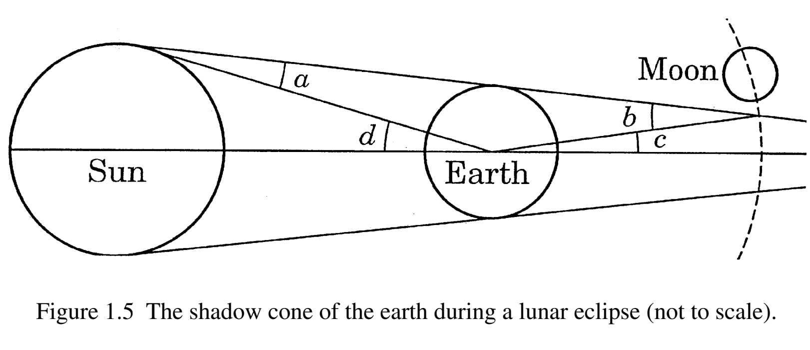

Figure 1.5 The shadow cone of the earth during a lunar eclipse (not to scale).

a plane section of the shadow cone, one can readily see the simple relation that exists between the angles a, b, c, and d. In the triangle moon-earth-sun, one has $a + b = c + d$, that is, the sun's parallax plus the moon's parallax is equal to the sun's angular radius plus the semidiameter of the earth's shadow. Since the sun's parallax is much smaller than the moon's parallax, the latter is therefore almost equal to the sum of the apparent semidiameters of the sun and the shadow. Thus, letting $a = 0'$, Hipparchus found that the distance of the moon was 59 times the earth's radius. However, assuming a solar parallax of $7'$, the smallest perceptible parallax, he found that distance to be 67 ⅓ times the earth's radius.[9]

Although these evaluations were made during the third and second centuries B.C., they look surprisingly modern in the sense that they are neither a mere speculation nor an accumulation of brute facts. Indeed, the three natural philosophers—Aristarchus, Eratosthenes, and Hipparchus—assumed a reasonable physical model and then, from simple measurements only, they were able to deduce some information about the relative sizes and distances of the earth, moon, and sun. The importance of their work lies not so much in the numerical figures they obtained, but in the facts that the relevant questions were asked and that they were formulated correctly. Such an approach, which was also favored by the Sicilian polymath Archimedes, lies at the core of modern science; it is unfortunate that it did not survive the Hellenistic period and had to be rediscovered at the end of the Middle Ages.

Of great historical importance also is the work of the Christian philosopher Johannes PHILOPONUS, who taught in Alexandria in the first half of the sixth century A.D. and was one of the last great commentators of Aristotle. His conception of the laws of motion, opposed to that of Aristotle, is particularly interesting. According to the latter, a body can move only if a mover exercises upon it an action at every instant of the motion; if left alone, it will not continue to move. The fact that missiles—such as stones and arrows—go on moving for some time after having been projected was assumed to be due to the contact with the surrounding air, to which the mover had imparted some of its moving power. Philoponus' innovation was to suggest instead that the continuance of the motion of a projectile was due to the action of a certain immaterial force—later called the "impetus"—which was communicated to the projectile by the mover. This new idea about forced motion had a considerable impact on physical doctrine in the Middle Ages—both in the Muslim world and in the Latin West—and played an important part in the gradual disintegration of Aristotelian orthodoxy. However, of greatest importance are Philoponus' cosmological views, based on the Judeo-Christian doctrine of creation. Thus admitting that the world was created by God from nothing and will be destroyed, he vehemently attacked Aristotle's assumption that the celestial region beyond the moon was immutable. In particular, he advocated the idea that the sun and the stars did not consist of ether but were made of the same stuff as the earth. He also claimed that the difference among stars in magnitude, color, and brightness was to be found in the composition of the matter of which the stars were constituted, being sources of fire of the same kind as terrestrial fires. Moreover, he declared that all matter in the universe is nothing

[9] See A. Van Helden, *Measuring the Universe* (Chicago: University of Chicago Press, 1985), 12–13.

but tri-dimensional extension, in which respect there is no difference between any of the celestial and the terrestrial bodies. Philoponus' cosmological views found no echo in his time, however, and about eleven centuries had to pass until observation showed that creation and decay were by no means confined—as was commonly believed—to the earth and its immediate surroundings.[10]

1.6 FROM THE DARK AGE TO THE RENAISSANCE

With the decline and fall of the Roman Empire, ancient philosophies gave place to a new religious, philosophical, and social movement—Christianity. Most of the early Fathers of the Church had little sympathy for anything that emanated from the heathen Greek and Roman world. For many centuries, therefore, anything that could not be reconciled with the Holy Scriptures was rejected with horror and scorn. Thus the earth became flat again; the heaven was no longer a sphere but a tent or tabernacle; and the sun did not pass under the earth during the night, but traveled laterally round its northern parts as if hidden by a wall. It was also widely believed that the sun, moon, and stars were moved in their orbits by angels, who had to carry on this work until the last day. Although this type of cosmology continued to flourish during the Middle Ages, some writers did study the works of the Greek philosophers, and they were not afraid to accept some of the teaching of antiquity. One of the most eminent figures of the transition period between Antiquity and the Middle Ages, Anicius Boethius (c. 480–524), is often called "The Last Roman." He translated several Greek scientific works into Latin, the only language common to the learned West. Boethius translated Ptolemy's *Almagest* into Latin, but this Latin translation was lost shortly after. As a result, astronomers of the early Middle Ages in the Latin West were ignorant of the epicycle theories of the planets.[11] The scientific heritage of that period was fully displayed by the encyclopedist Isidorus Hispalensis (c. 560–636), archbishop of Seville, who repeatedly referred to the spherical shape of the earth in his writings, although they otherwise contain passages that may be reconciled only with belief in a flat earth.

Another important step forward was made by an English monk, the Venerable Bede (673–735), who stoutly maintained that the earth is a sphere and cited as proof the fact that stars visible in one latitude are invisible in another; borrowing heavily from the Latin author Pliny the Elder (23–79), he also gave a detailed account of the nonuniform apparent motions of the planets circling round it. From about the ninth century geocentrism and the rotundity of the earth may be considered to have been acceptable again in the Christian West. In the early Middle Ages, from the eighth to the twelfth century, the geoheliocentric system attributed to Heraclides also enjoyed a widespread popularity propagated by several Latin authors—such as Martianus Capella, who wrote a compendium of science and philosophy in the first

[10] See especially S. Sambursky, ed., *Physical Thought from the Presocratics to the Quantum Physicists: An Anthology* (New York: Pica Press, 1975); R. Sorabji, ed., *Philoponus and the Rejection of Aristotelian Science* (Ithaca, N.Y.: Cornell University Press, 1987).

[11] It was not until the 1160s that a poor Latin translation of the *Almagest* was made in Sicily from Greek; soon afterward, in 1175, a better translation was made from Arabic to Latin by Gerard of Cremona (1114–1187) in Toledo, Spain.

half of the fifth century. Let us also mention the work of Johannes Scotus ERIGENA (c. 810–877), an Irish-born philosopher active in France in the 850s and 860s, who referred to "Jupiter, Mars, Venus, and Mercury, which ceaselessly pursue their orbits around the sun (*qui circa solem volvuntur*)." Historians have disagreed about whether Erigena meant to claim that these four planets move on heliocentric orbits, or merely that they differ from chilly Saturn in that they are near the sun, are much akin to it, and traverse the same region of the heavens that it does. It is unfortunate that in the original manuscript Erigena's famous passage was not accompanied by a graph.[12]

Meanwhile, carrying the banner of Islam, Arabic tribes were suddenly fused into a powerful nation during the seventh century. War and conquest were rapidly followed by intense intellectual activity in Syria and then in Iraq. The rise of the Abbasid caliphate (750–1258) inaugurated the greatest period of Islamic rule, and Baghdad became the center of a brilliant civilization which spread over the entire Muslim world. Old Indian and Greek books were translated into Arabic during the eighth and ninth centuries. Ptolemy's *Almagest* was translated into Arabic for the caliph al-Ma'mun (c. 786–833) in the late 820s, while large observatories were being built in Baghdad and Damascus. AL-BATTANI (c. 858–929), perhaps the greatest Islamic astronomer, tested many of Ptolemy's results, brought important ameliorations to them, and published improved tables of the sun and the moon. From the same time AL-SUFI (903–986) is chiefly known for his catalog of stellar magnitudes. This work was particularly valuable since its author carefully recorded the magnitudes "as they were seen by his own eyes," whereas other star catalogs of that period had simply borrowed all the magnitudes from the *Almagest*.

The next astronomical center of that time and region was at Cairo, where Ibn YUNUS (c. 950–1009) published a set of astronomical and mathematical tables, the *Hakemite Tables*, which remained the standard ones for about two centuries. Another important observatory was built at Maragha in northwest Iran by the Mongol prince Hulagu Khan (c. 1217–1265), a grandson of Genghis Khan (1162–1227). Its main contribution was a volume of new astronomical tables published under the direction of Nasir al-Din AL-TUSI (1201–1274) in 1271, and known as the *Ilkhanic Tables*. But the most productive observatory in western Asia was that of the Muslim ruler and scholar ULUGHBEK (1394–1449), a grandson of the Mongol conqueror Timur (1336–1405). Working at Samarkand with his assistants, Ulughbek made a star catalog from observations with a 40-meter sextant fixed on the meridian and other precision instruments. This was probably the first substantially independent catalog of stellar positions made since the time of Hipparchus sixteen centuries before. He also published fresh tables of the planets, and did his own amazingly accurate calculations of the length of the year. Unfortunately, Ulughbek was the victim of a cultural and religious backlash: He was murdered at the instigation of his own son, and the Samarkand observatory was reduced to ruins by the beginning of the sixteenth century, although his

[12] See especially P. Duhem, *Le système du monde*, vol. 3 (Paris: Hermann, 1915–1958), 58–62; E. von Erhardt-Siebold and R. von Erhardt, *The Astronomy of Johannes Scotus Erigena* (Poughkeepsie, N.Y.: Vassar College Press, 1940). For an overall picture, see S. C. McCluskey, *Astronomies and Cultures in Early Medieval Europe* (Cambridge: Cambridge University Press, 1998).

astronomical work was saved and published to posthumous acclaim in Western Europe.[13]

During the tenth century, astronomy and other branches of knowledge also made some progress in Muslim Spain and the opposite coast of Africa. A great library and an academy were founded at Cordoba about 970, and similar establishments sprang up in Toledo, Seville, and Morocco. Thence, the fame of Arabic astronomy began slowly to spread through Spain into other parts of western Europe. Toledo, despite its reconquest by Christendom in 1085, long remained an important center of Arab and Hebrew culture, where a true spirit of collaboration lingered on among Jewish, Christian, and Moorish scholars. The most important work produced by these astronomers was the volume of astronomical tables known as the *Toledan Tables* (1080), of which translations and adaptations were widely distributed in Europe. Western knowledge of astronomy was very much increased by the activity of Alfonso X (1221–1284), "the Wise," king of Castile and León. He collected at Toledo a body of scholars, mostly Jews, who calculated a set of new astronomical tables for predicting positions of planetary bodies. These *Alfonsine Tables* (1272) spread rapidly through Europe and were in use for about three centuries, up to the middle of the sixteenth century. To Alfonso is also due the publication of a vast encyclopedia of astronomical knowledge compiled by a similar group from Arab sources.

One of the last significant astronomers of Muslim Spain was al-Bitruji, known to the Latins as ALPETRAGIUS (died 1204). Philosophically, he objected to Ptolemy's planetary system on the grounds that it violated Aristotle's physical principles. He therefore advocated an alternative model for planetary motion that was based on concentric spheres rotating about inclined axes. This work, which was translated into Latin in 1217, remained influential for several centuries. In fact, at the beginning of the twelfth century, a great wave of translations from Arabic to Latin had already begun, partly of original Arabic books, partly of Arabic translations of Greek books. The physical works of Aristotle, among which *De caelo* is by far the most important, and Ptolemy's books thus became available to western scholars. The influence of Aristotle over medieval thought soon became almost supreme, and by the end of the thirteenth century most of his cosmological views, or supposed views, were firmly established in the Latin West, with Church approval. With the notable exception of Robert GROSSETESTE (c. 1175–1253), chancellor of Oxford University, and a few others who denied the existence of Aristotle's fifth element, it was therefore widely accepted that the four elements—earth, water, air, and fire—filled the sublunar region of the sky, while the celestial region from the moon outward was composed exclusively of an extraordinary substance, a special ether or fifth element. The earth was of course resting at the center of the universe, which was spherical in shape and of finite extent (see figure 1.6). Not unexpectedly, beyond the general assertion that rotating heavenly spheres move the stars and planets, opinion among medieval thinkers as to the final causes of these rotations varied widely. Of particular interest is the *Guide for the Perplexed*, in which the Jewish philosopher

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[13] See K. Krisciunas, *Astronomical Centers of the World* (Cambridge: Cambridge University Press, 1988), 23–39.

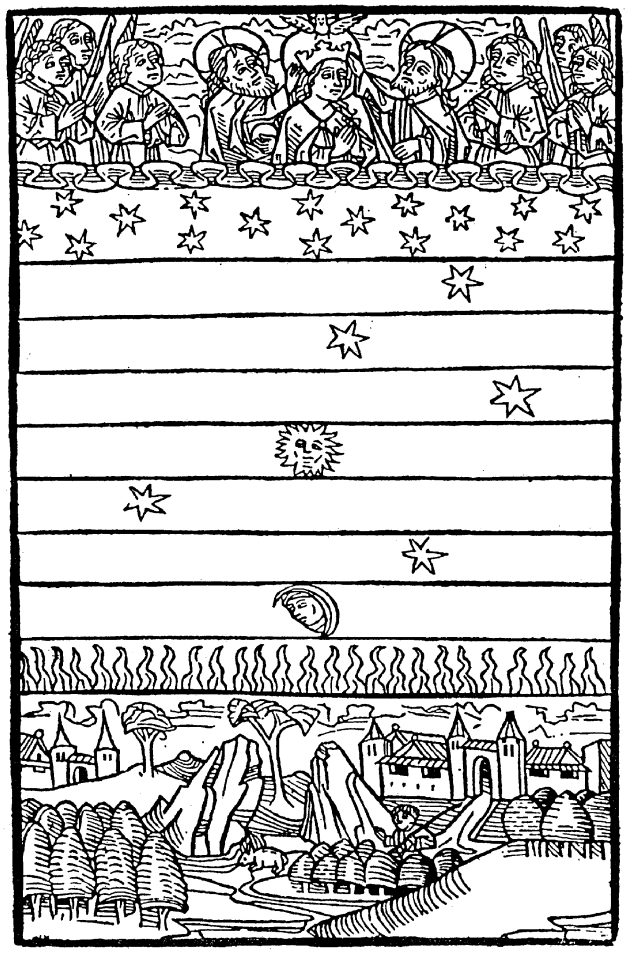

Figure 1.6 A Christian view of the universe around 1350. In the lowest layer we see the elements earth, water, and air, and their creatures. Just above is the sphere of fire, which is a pure but invisible element. Above these four elements rise the spheres of the seven planets and that of the fixed stars, all of which are apparent to our eyes. Above this level lies the Christian heaven, which is not perceptible to our senses. In this artistic depiction we observe the Son with His Crown, the Holy Ghost in the familiar form of a dove, and the Father. Note that for purposes of symmetry the Father is made two figures, just as there are two symmetrical groups of angels. This type of cosmology, which has the virtue of simplicity and completeness, was commonly accepted until the seventeenth century. From S. K. Heninger, Jr., *The Cosmographical Glass: Renaissance Diagrams of the Universe* (San Marino, Calif.: Huntington Library, 1977). By permission of the Huntington Library.

Moses Maimonides (1135–1204) embraces different patterns of interpretation of heavenly phenomena. His cosmology is basically Aristotelian, and he held that rotating spheres moved the planets by mechanical transmission of motion through contact. Movement of the spheres proceeded from another causation: Elaborating on the thought of his Muslim predecessors, Maimonides identified the separate intelligences of Aristotelianism moving the heavenly spheres with the angels of Scripture. These views influenced the Dominican theologian Thomas Aquinas (1227–1274) and, through him, the whole thought of Latin Christendom. In fact, such terms as "moving intelligences" or "angels of the spheres" were still familiar to all in the sixteenth and seventeenth centuries.

Thirteenth-century astronomy in western Europe was concerned mainly with a debate as to the relative merits of two rival planetary systems. The first was derived from the works of Aristotle and Alpetragius, where it was assumed that the planets were carried around on concentric spheres. In the second system, derived ultimately from Ptolemy's book *Hypotheses of the Planets*, the planets were assumed to be carried around by a system of material eccentric and epicyclic spheres, whose centers did not coincide with the earth's center. The Ptolemaic system was quickly recognized as being the best geometric device for "saving the astronomical appearances." The practical astronomers, who inevitably demanded quantitative results, thus had no choice but to retain the eccentrics and epicycles of Ptolemaic astronomy, even though they could not be easily reconciled with the principles of the only adequate system of physics known—that of Aristotle. By the end of the thirteenth century the system of concentric spheres had been largely discarded, and scholastic philosophers increasingly came to assume the existence of material eccentrics and epicycles. Special consideration among the medieval astronomers may be given to the Provençal Jew Levi ben Gerson, also known as Gersonides (1288–1344), who was the first to criticize the faulty methodology of medieval science. Specifically, he measured the changes in the apparent brightnesses of the planets with the goal of refuting the Ptolemaic system. (He developed specific instruments for this purpose, essentially pinholes and the camera obscura.) Since the results of his observations did not fit Ptolemy's planetary models, Gersonides therefore concluded that the epicyclic hypothesis must be rejected as contrary to the phenomena. He also rejected the model suggested by Alpetragius, who had objected to epicycles for Aristotelian reasons, but was unable to devise a better one. Gersonides' contention was that "no argument can nullify the reality that is perceived by the senses; for true opinion must follow reality, but reality need not conform to opinion"—certainly not the usual position in the scholastic age.[14] During the fourteenth and fifteenth centuries, even more radical developments may have been suggested by ancient Greek speculations, in particular the earth's daily rotation and the semiheliocentric system in which Venus and Mercury revolve around the sun while the sun itself revolves around the earth. The concept of geocentrism remained unchallenged until the 1510s, when the Polish astronomer Nicolaus Copernicus (1473–1543) revived Aristarchus' heliocentric hypothesis.

[14] See B. R. Goldstein, *Theory and Observation in Ancient and Medieval Astronomy* (London: Variorum Reprints, 1985).

Although few considered the problem during the Middle Ages, prior to the seventeenth century scholars were divided on the nature of the light emanating from the fixed stars and the planets.[15] Of particular interest is the work of the Cairo astronomer and optician Ibn al-Haytham, known in the West as ALHAZEN (965–1038), who pointed out that the stars and planets, unlike the moon, always exhibited the bright shape of a complete circle regardless of their positions with respect to the sun, and regardless of the observer's location. (The phases of Venus had not yet been observed.) He therefore concluded that the stars and planets were selfluminous, and that the moon was unique among heavenly bodies in being the only one that borrowed its light from the sun.[16] The Persian physician and philosopher Ibn Sina, known to the Latins as AVICENNA (980–1037), did also concede that the moon received its light from the sun and that the stars and planets were self-luminous. Ibn Rushd, also known as AVERROËS (1126–1198) and perhaps the most influential Muslim philosopher in Spain, agreed that the moon had its light from the sun, but argued for the sun as the sole source of light for all stars and planets; the Franciscan friar Roger BACON (c. 1220–1292) in Oxford was of the same opinion. Subsequently, the Dominican friar ALBERTUS MAGNUS (c. 1200–1280), also known as Albert of Cologne, and the scholastic philosopher ALBERT OF SAXONY (c. 1316–1390) developed various arguments in defense of the idea that the sun illuminated the planets. Among other problems, they had to explain how the planets could appear visibly different and yet receive their light from the same source. Albert of Saxony coped with this problem by assuming that the solar light can penetrate the diaphanous planetary matter, each planet differing in its ability to absorb light. This was a most popular explanation of planetary light: the planets were visible to us because they were partly transparent and, hence, could be filled more or less completely with the sun's light. The Norman polymath Nicole ORESME (c. 1325–1382), a scholar in Paris and later bishop of Lisieux, thought that the self-luminosity option was more probable.

Interest in the light source of the stars became manifest in the late sixteenth century, but again scholars were hardly of one mind. Some were convinced that the fixed stars received their light from the sun because they were not so far off that the sun's light could not reach them. Others believed that the solar light was not the only source of stellar brightness but that each star might have a small amount of light within itself. Thomas DIGGES (1545/46–1595) and Giordano BRUNO (1548–1600) were the first natural philosophers to break with these traditional views by interpreting the fixed stars as suns, and hence as self-luminous bodies. In 1576 Digges published an English version of Copernicus' *De revolutionibus orbium coelestium* (1543), adding to his translation the assertion that the heliocentric universe should be conceived as infinite, with the fixed stars located at varying distances throughout

[15] See E. Grant, *Planets, Stars, & Orbs: The Medieval Cosmos, 1200–1687* (Cambridge: Cambridge University Press, 1994), 390–421.

[16] Alhazen was actually the first to experiment with different media in the hope of finding a working theory of reflection and refraction. His disciple WITELO, a Polish physicist who spent most of his life in Italy, also tried to establish the laws of refraction. In his *Perspectiva*, a huge treatise on optics of the 1270s, Witelo explained the twinkling of stars as due to moving air currents in the earth's atmosphere and showed that the effect was intensified when stars were viewed through running water. See H. C. King, *The History of the Telescope* (Cambridge, Mass.: Sky Publishing Corporation, 1955), 26.

infinite space. Thus Digges clearly perceived that, the moment the displacement of the earth was conceded, there was no longer any necessity for picturing the stars as attached to a celestial sphere at a finite distance from the earth. Contrary to Digges, Bruno was a mystic, and his own speculations had their roots in some earlier suggestion by the Rhinelander theologian Nicolaus CUSANUS (1401–1464), who had been led to a belief that the universe has neither center nor circumference; that it is not infinite, yet it cannot be conceived as finite, since there are no limits within which it is enclosed; and that the earth, which cannot be the center of the universe, must in some way be in motion, as are all other bodies in space, with a velocity that is not absolute but relative to the observer. Actually, it was this doctrine of relativity, in space and in motion, that served as the background for Bruno's conception of an infinite universe and innumerable worlds.[17] The essential conclusions of Bruno's work are that not only does the earth move round the sun but the sun itself moves; that our planetary system is not the center of the universe, and that the latter is of infinite size and the worlds therein without number; and that the stars are at large but varying distances from the sun and are themselves centers of planetary systems. These assertions, which were published in England in 1584, marked the change from medieval to modern scientific thought. Betrayed and arrested in Venice, Bruno was transferred to Rome in 1593 and remained in prison for seven years. Then, after a long trial, he was burned at the stake in Rome for his writings which, in addition to containing religious and political heresies, supported the new Copernican system and opposed the traditional Aristotelian cosmology.

1.7 THE EMERGENCE OF MODERN ASTRONOMY

About the end of the sixteenth century and the beginning of the seventeenth century were made the first decided advances since antiquity in observational astronomy. In this field the leading names are those of Tycho BRAHE (1546–1601) and Galileo GALILEI (1564–1642), the former relying upon the naked eye for his measurements, the latter on his recently built refracting telescope.

In 1572 Tycho observed a new star and, failing to detect parallax in his observations, he correctly deduced that it was located well beyond the planets. The star's eighteen-month life span left a considerable impact since it cast serious doubt on the existence of an eternally unalterable celestial region. His observations of a brilliant comet in 1577 also convinced Tycho that its parallax placed it well beyond the sublunar region where comets were supposed to be confined. This was another severe blow to the medieval belief that the celestial region beyond the moon's orbit was immutable. However, because his observations did not disclose a stellar parallax, Tycho rejected the Copernican theory of the earth's revolution. He proposed as a compromise that the sun revolved around a stationary earth, while all the planets—Mercury, Venus, Mars, Jupiter, and Saturn—went around the sun.

[17] For English translations of this and other pioneering works, see M. K. Munitz, ed., *Theories of the Universe: From Babylonian Myth to Modern Science* (New York: Free Press, 1957).

Galileo's first contribution to astronomical discovery was made in 1604, when a new star appeared in Ophiuchus, and was shown by him to be without parallax, a result confirming Tycho's conclusions that changes take place in the celestial region beyond the planets. With his telescopic observations made in the 1610s, Galileo added to this a picture of celestial bodies that exhibited surface irregularities: the moon, whose mountains and valleys made it akin to the earth; and the sun, whose spots continually changed in shape and then disappeared while others again succeeded them. The discovery of sunspots is of particular importance because it caused irremediable damage to the Aristotelian principle of stability and incorruptibility of the heavens beyond the moon. Of the new discoveries, Galileo's telescopic observations of the phases of Venus and of the satellites of Jupiter were perhaps the most dramatic events in transforming heliocentrism from a convenient hypothesis for mathematicians into a most plausible physical description of our planetary system. This was a deadly blow to the traditional geocentric and anthropocentric universe.

In 1616 the Copernican doctrines were thus declared "false and absurd, formally heretical and contrary to Scripture" and Galileo was admonished to abandon these opinions. In 1632 Galileo published his epoch-making treatise *Dialogo sopra i due massimi sistemi del mondo* (Dialogue on the two chief world systems), that is, the Ptolemaic and the Copernican (see figure 1.7). Although the book came out bearing both the Roman and the Florentine imprimaturs, it was soon suspended and its sale prohibited on the ground that it was a compelling and unabashed plea for the heliocentric system.[18] In 1633 Galileo was condemned by the Roman Inquisition for believing and holding that the Copernican doctrines were true and, in punishment, was required to "abjure, curse, and detest the aforesaid errors" and forced to spend the last eight years of his life under house arrest. While confined to his villa at Arcetri, near Florence, he published in 1638 his *Discorsi e dimostrazioni matematiche interno a due nuove scienze* (Dialogue on two new sciences), in which he summarized the results of his early work with falling bodies and projectiles and presented his penetrating views on the principles of mechanics. This important work, which was not published in Italy but in Holland, paved the way for Newtonian mechanics.

Copernicus' heliocentric theory made continued support for the medieval geocentric cosmology untenable for the majority of astronomers, if not for the majority of scholastic philosophers. Yet Copernicus was a conservative because he did not venture to abandon the use of patterns of circular motion and indeed continued to make use of epicycles in describing planetary trajectories. The great contribution of Johannes KEPLER (1571–1630) was to improve the theory of planetary motion by replacing circles and epicycles by *ellipses* (see figure 1.8). He himself was not an observer, but he had great faith in the accuracy of the observations of his teacher, Tycho, which he had inherited at the time of Tycho's death. Although Kepler had strong mystical leanings, so that a large portion of his work is now unreadable, his

[18]After many unsuccessful attempts, the ban on Galileo's *Dialogue* and other books advocating heliocentrism was finally lifted in 1822; and after 1835 the names of Copernicus, Galileo, and Kepler no longer appeared on the *Index of Prohibited Books*.

claim to immortal fame rests upon his discovery of the following empirical laws of planetary motion:

1. Each planet describes an ellipse, with the sun being at one focus.
2. The speed of each moving planet changes with distance from the sun, so that the straight line joining each planet to the sun sweeps out equal areas in any two equal intervals of time.
3. The squares of the periods of revolution of any two planets (including the earth) about the sun are in the same ratio as the cubes of their mean distances from the sun.

Figure 1.7 Frontispiece of Galileo's *Dialogue on the Two Chief World Systems*, printed in Florence in 1632. The three figures are inscribed *Aristotle* (*left*), *Ptolemy* (*middle*), who carries a model of nested geocentric spheres, and *Copernicus* (*right*), who bears an emblem of his own heliocentric theory. Note that the last figure bears more resemblance to Galileo's portraits than to those of Copernicus. Courtesy of Owen Gingerich.

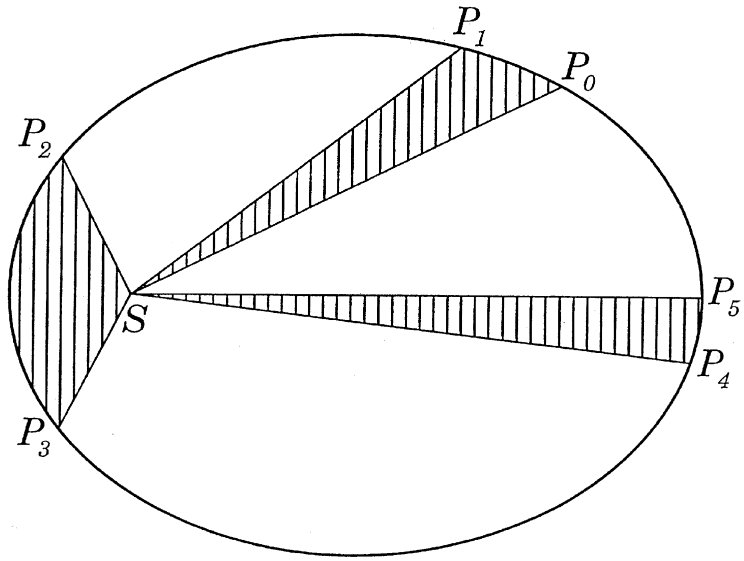

Figure 1.8 Kepler's law of equal areas. Planets sweep out equal areas in equal times. P_0P_1, P_2P_3, and P_4P_5 are distances along its elliptical orbit around the sun S traversed by the planet in equal times. The areas SP_0P_1, SP_2P_3, and SP_4P_5 are equal. The path presented here is far more elliptical than those pursued by the planets, which are very much more nearly circular.

(The "mean distance" in the third law is half the major axis of the ellipse.) Kepler announced his third law in 1619, ten years after he had given the first two. Not unexpectedly, his books were promptly banned and placed on the Roman *Index of Prohibited Books*.

Although the geocentric system continued to command widespread support throughout the seventeenth century, heliocentrism with its Keplerian modifications was cautiously gaining acceptance. Attempts were thus made to find out what causes the planets to move on their elliptic orbits with the sun occupying one of the focal points. The solution proposed by the French philosopher René DESCARTES (1596–1650) in 1644 was eagerly accepted.[19] It assumes that all space is filled with a fluid, or ether, the parts of which act on each other and generate a whole spectrum of vortices of different size, velocity, and density. There is an immense vortex around each star and, in particular, around the sun, which carries in its circular motion the earth and the other planets. Each of these planets is located, in turn, in a smaller vortex by which gravitational attraction is produced. Descartes made no attempt

[19]From 1629 to 1649 Descartes was to remain almost permanently in Holland, making only three short visits to France during all this time. Most of his more important works were written and published in Holland, where he could profit from greater intellectual freedom. But even in this land of toleration he was to meet with enmity, the bitterest coming from the president of Utrecht University. Late in 1649 Descartes moved to Sweden at the invitation of Queen Christina (1626–1689), but he caught a severe chill there and died after a short illness.

to reconcile his theory with Kepler's laws. In fact, it was unsupported by any experimental evidence and did not explain a single phenomenon satisfactorily. Yet "Cartesianism" became extremely fashionable, especially in France, and its vogue undoubtedly contributed to the overthrow of the Aristotelian system.

Descartes' vortex theory required one motion to be the cause of another and explained the mutual attraction of the sun and the planets in terms of actual bodily motions. As early as the 1660s, however, Isaac NEWTON (1642–1727) rejected Descartes' hypothesis of material vortices as the cause of gravitation. According to him, gravity is the power of attraction that one body exercises upon another without the first being in motion or coming in contact with the second. Although this approach raises the problem of action at a distance, which Newton properly acknowledged, it has the merit of fitting the observed phenomena.[20] What Newton brought to the subject is to be found in the simplicity that his *laws of motion* combined with the principle of *gravitational attraction* were able to introduce into the description of planetary orbits and ordinary terrestrial phenomena. Newton's unique achievement was to prove that the force that causes a stone to fall on earth is also that which keeps the planets in their orbits. This is expressed in Pope's famous epigram:

> Nature and Nature's laws lay hid in Night,
> God said, Let Newton be, and all was light,

which celebrates the illumination of nature by Newton's mechanical approach to the physical world.

When, in 1687, Newton published his epoch-making treatise *Philosophiae naturalis principia mathematica*, or "Mathematical Principles of Natural Philosophy" (figure 1.9), the medieval geocentric world had become utterly irrelevant because it no longer represented a viable alternative to a world in which gravitational attraction forces each planet to move along an ellipse. In other words, Newton's theory of gravitation made physical sense of heliocentrism while providing a simple, natural derivation of Kepler's empirical laws from first principles alone. The law of gravity is basically simple: it merely states that *two bodies attract each other with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them*. The success of the theory was all the more evident that the general solution of the two-body problem was found to be a conic (i.e., a circle, an ellipse, a parabola, or a hyperbola), in perfect agreement with the

[20]It was not until 1915 that Albert EINSTEIN (1879–1955) resolved this dilemma by transforming Newton's theory of action at a distance, in which gravity acts instantaneously across the entire universe, into a local-action theory in which gravity is equivalent to a curvature of four-dimensional spacetime. Specifically, whereas Newton assumed that space and time form the stage upon which mechanical phenomena are displayed, Einstein took gravity as an intrinsic feature of spacetime itself. In his *general theory of relativity*, as it became known, the geometrical properties of this four-dimensional continuum are determined by the masses present in space and time, and these geometrical properties in turn have a causal influence on the motions of these masses. An important inference we can draw from Einstein's 1915 theory is the way ripples in the fabric of spacetime travel. Detailed calculations have shown that some revolving bodies, such as compact binary star systems, emit a weak gravitational field in the form of waves (see section 6.6). These waves propagate with the speed of light. Action at a distance is therefore avoided, and causality is restored.

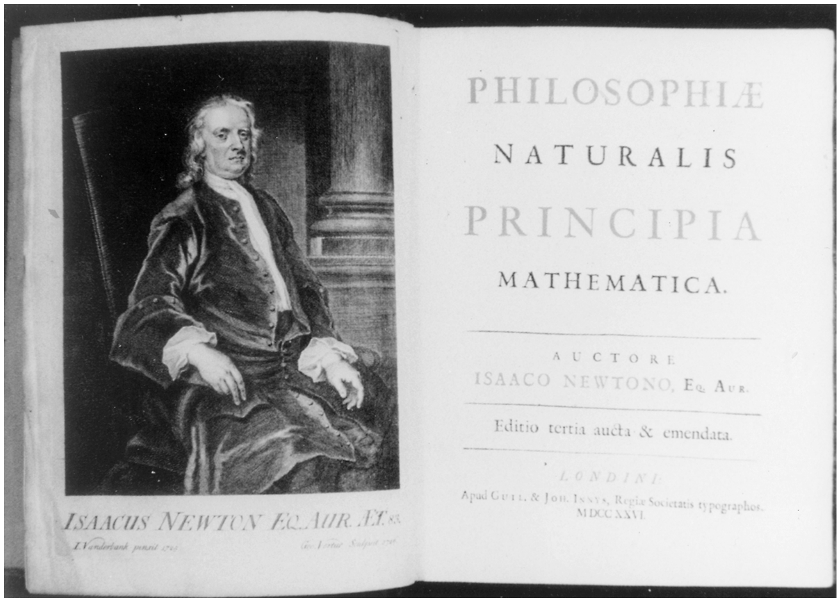

Figure 1.9 Sir Isaac Newton graces the frontispiece of the third edition of his *Mathematical Principles of Natural Philosophy*, published in London in 1726. Courtesy of Owen Gingerich.

observed trajectories of different comets. Yet, as was noted by Newton: "Hitherto we have explained the phenomena of the heavens and of our sea by the power of gravity, but have not assigned the cause of this power." Pointing out that he had made no unreasonable hypothesis, he further concluded: "And to us it is enough that gravity does really exist, and act according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea." Newton's theory is of great philosophical importance because it is the first successful attempt to explain the universe and its processes without reference to gods or animistic conceptions.

By the time geocentrism and terrestrial immobility had lost all credibility, it was widely accepted that the fixed stars were self-luminous bodies, the sun being one among the multitude of stars. However, because no stellar parallax could be detected from the earth's orbital motion round the sun, enormous arbitrary distances had to be assumed between the sun and the fixed stars. The problem was discussed by the Dutch polymath Christiaan HUYGENS (1629–1695) in his treatise *Cosmotheoros*; his efforts at measuring the distance of Sirius are particularly noteworthy. (The work was published posthumously in 1698.) Lacking any information about the global properties of stars, he assumed that his test star, Sirius, was exactly similar to the sun. If so, then, he correctly deduced that its distance from us should be as much greater than that of the sun as its apparent diameter was less than the diameter of the solar disk. In practice, to compare the sun and Sirius, he gradually lessened the sun's diameter in his telescope, closing one end of his twelve-foot tube with a plate that had a variable hole in its middle. Reducing the hole's diameter till the sun appeared of the same brightness as Sirius, he found that he had to make its diameter but the 27,664th part of the diameter of the observed solar disk. In our modern notation, he evaluated the distance of Sirius at about 27,664 AU whereas its distance is actually close to 546,000 AU. (Here AU denotes the astronomical unit, that is, the mean sun-earth distance.) Although we know that Huygens' evaluation was vitiated by an inadequate assumption about the global properties of Sirius, this observational work should not be ignored, because it is quite illustrative of the spirit and methods of the Scientific Revolution that changed our views of the universe.