CHAPTER 11

Copernicus Incites a Revolution

On his deathbed in 1543 Nicholas Copernicus received the first published copy of his book, *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*). In this seminal work Copernicus proposed a sun-centered or heliocentric cosmology with a moving earth rotating once a day on its own axis and orbiting the sun once a year. In 1543 every culture in the world placed the earth instead at the center of its cosmology. In breaking so radically with geocentrism, received astronomical wisdom, and biblical tradition, Copernicus launched the Scientific Revolution and took the first steps toward the formation of the modern scientific worldview.

The Scientific Revolution represents a turning point in world history. By 1700 European scientists had overthrown the science and worldviews of Aristotle and Ptolemy. Europeans in 1700—and everyone else not long afterwards—lived in a vastly different intellectual world than that experienced by their predecessors in, say, 1500. The role and power of science, as a way of knowing about the world and as an agency with the potential of changing the world, likewise underwent profound restructurings as part of the Scientific Revolution.

The historical concept of *the* Scientific Revolution of the sixteenth and seventeenth centuries emerged only in the twentieth century. The Scientific Revolution was initially thought of as an intellectual transformation of our understanding of nature, a conceptual reordering of the cosmos that entailed, in the felicitous phrase, moving from a closed world to an infinite universe. As scholars have delved deeper into the subject, the unquestioned unity and reality of *the* Scientific Revolution or a Scientific Revolution began to break down. The Scientific Revolution as simply an episode in the history of scientific ideas is long a thing of the past. For example, any treatment of the Scientific Revolution must now address not just a triumphant astronomy or mechanics but the "occult" sciences of magic, alchemy, and astrology. Ideological arguments for the social utility of science prove to be a fundamental feature of the Scientific Revolution, and the emergence of new scientific methods—notably experimental science—likewise seems a key property of the "new science" of the sixteenth and seventeenth centuries. Changes in the social and institutional organization of contemporary science are now seen as additional defining elements of the Scientific Revolution. The current interpretative stance rejects any simple notion of the Scientific Revolution as a unitary event with clearly defined chronological or conceptual boundaries. Historians now tend to treat the Scientific Revolution as a useful conceptual tool, setting the episode in a broader historical context as a complex and multifaceted phenomenon to be studied through a variety of approaches.

The New World of the European Renaissance

The social context for science in Europe in the sixteenth and seventeenth centuries had changed in several dramatic ways from the Middle Ages. The Military Revolution, the European voyages of exploration, and the discovery of the New World altered the context in which the Scientific Revolution unfolded. The discovery of the Americas generally undermined the closed Eurocentric cosmos of the later Middle Ages, and the science of geography provided a stimulus of its own to the Scientific Revolution. With an emphasis on observational reports and practical experience, new geographical discoveries challenged received authority; cartography thus provided exemplary new ways of learning about the world in general, ways self-evidently superior to mastering inherited dogma from dusty manuscript books. Many of the scientists of the Scientific Revolution seem to have been involved in one fashion or another with geography or cartography.

But printing was a different matter. In the late 1430s Johannes Gutenberg, apparently independently of developments in Asia, invented printing with movable type, and the spread of this powerful new technology after 1450 likewise altered the cultural landscape of early modern Europe. The new medium created a "communications revolution" that increased the amount and accuracy of information available and made scribal copying of books obsolete. Producing some 13,000 works by 1500, printing presses spread rapidly throughout Europe and helped to break down the monopoly of learning in universities and to create a new lay intelligentsia. Indeed, the first print shops became something of intellectual centers themselves with authors, publishers, and workers rubbing shoulders in unprecedented ways in the production of new knowledge. Renaissance humanism, that renowned philosophical and literary movement emphasizing human values and the direct study of classical Greek and Latin texts, is hardly conceivable without the technology of printing that sustained the efforts of learned humanists. Regarding science, the advent of printing and humanist scholarship brought another wave in the recovery of ancient texts. Whereas Europeans first learned of ancient Greek science largely through translations from the Arabic in the twelfth century, in the later fifteenth century scholars brought forth new editions from Greek originals and uncovered influential new sources, notably Archimedes. Similarly, printing disseminated previously recondite handbooks of technical and magical "secrets" that proved influential in the developing Scientific Revolution. And, notably, the technology of printing produced a huge impact on contemporary science without any corresponding input from science on printing technology.

Particularly in Italy, the revival of cultural life and the arts in the fourteenth and fifteenth centuries commonly known as the Renaissance must also be considered as an element of changed conditions of the early modern period. The Italian Renaissance was an urban and comparatively secular phenomenon, aligned with courts and courtly patronage (including patronage by church prelates), but not the university. One associates the great flourish of artistic activity of the Renaissance with such painting talents as Donatello (1386–1466), Leonardo da Vinci (1452–1519), Raphael (1483–1520), and Michelangelo (1475–1564). In comparison with medieval art, the use of perspective—a projection system that realistically renders the three dimensions of space onto the two dimensions of a canvas—represents a new feature typical of Renaissance painting, and through the work of Leon Battista Alberti (1404–1472), Albrecht Dürer (1471–1528), and others, artists learned to practice mathematical rules governing perspective. The architect Filippo Brunelleschi (1377–1446) contributed to these developments, and he extended Renaissance sensibilities and energy into architecture, most famously in the great dome he erected on the cathedral in Florence. So noteworthy was this development that historians have been inclined to place Renaissance artists at the vanguard of those uncovering new knowledge about nature in the fifteenth and sixteenth centuries. Whatever one may make of that claim, early modern artists needed accurate knowledge of human muscular anatomy for lifelike renditions, and an explosion of anatomical research in the Renaissance may be attributed to this need in the artistic community.

Indicative of these changing times, the great Renaissance anatomist Andreas Vesalius (1514–1564) published his influential anatomical opus, *De humani corporis fabrica* (*On the Fabric of the Human Body*), in 1543, the same year that Copernicus published his tome on the heavenly spheres. Vesalius was a military surgeon and his anatomical expertise probably owed as much to the Military Revolution and to the new sorts of wounds inflicted by firearms as it did to any aesthetic requirements of Renaissance art. Vesalius's drawings were crafted to convey information about the body rather than to depict the body as it might actually appear. Other Italian anatomists continued to refine their skills and make anatomical discoveries. Bartolomeo Eustachi (d. 1574) and Gabriel Fallopius (1523–1562) gave their names to previously unknown tubes in the body, and in 1559 Realdo Colombo (1520–1560) postulated the lesser or pulmonary circulation of the blood from the heart through the lungs. Fabricius of Acquapendente (1537–1619) uncovered valves in the veins. These anatomical developments were capped by the discovery of the circulation of the blood by the English physician William Harvey (1578–1657). Harvey studied in Italy and was elected a fellow of the Royal College of Physicians in London where he lectured on anatomy. By careful observations of the slowly beating hearts of dying animals, along with estimates of the quantity of blood that leaves the heart, Harvey arrived at the conclusion that the arterial and venous blood vessels form a connected circulatory system. The publication of his discovery in 1628 was a revolutionary outcome of the fertile tradition of Renaissance anatomy. Indeed, these revisions of the anatomical doctrines inherited from Galen and Aristotle reflect the comprehensiveness of the Scientific Revolution in the Europe of the sixteenth and seventeenth centuries.

Magic and the occult sciences in the Renaissance constituted a defining element of contemporary science and natural philosophy. The importance of magic was overlooked in earlier histories of science, but more recent scholarship has made magic more central to the story of the Scientific Revolution. The occult sciences of the Renaissance included astrology, alchemy, demonology, divination, magic, Neoplatonism, Rosicrucianism (which involved secret societies and occult symbols), and the Cabala (concerning secret mysteries in the Bible). The range of magical activities varied considerably in the early modern period, from proscribed contact with the forces of evil through black magic to "natural" or "mathematical" magic, which had to do with remarkable machines or technical processes (such as burning mirrors or magnets) that produced astounding effects. Despite our prejudices against magic and the occult as irrational delusion and charlatanry, at its highest levels Renaissance magic and associated knowledge systems were serious spiritual and intellectual enterprises that embodied learned understanding of the natural world. The very notion of the occult involved a dual meaning, both as secrets shared among adepts and as secrets hidden in nature.

With the elaborate given name of Philippus Aureolus Theophrastus Bombastus Von Hohenheim the Swiss physician and alchemist Paracelsus (1493–1541) vehemently challenged the medical establishment and the reigning scholastic medical tradition. Paracelsus rejected most of ancient and Islamic medicine, and in so doing he struck at the heart of Aristotelian natural philosophy. His famous dictum that "the dose makes the poison" destroyed notions of innate properties, and his occult and practical knowledge of metals led him to their application in medical treatments, such as his use of mercury to treat syphilis, a disease new to Europe. Paracelsus's own notions proved influential, and in his way Paracelsus, like his contemporary Nicholas Copernicus, has

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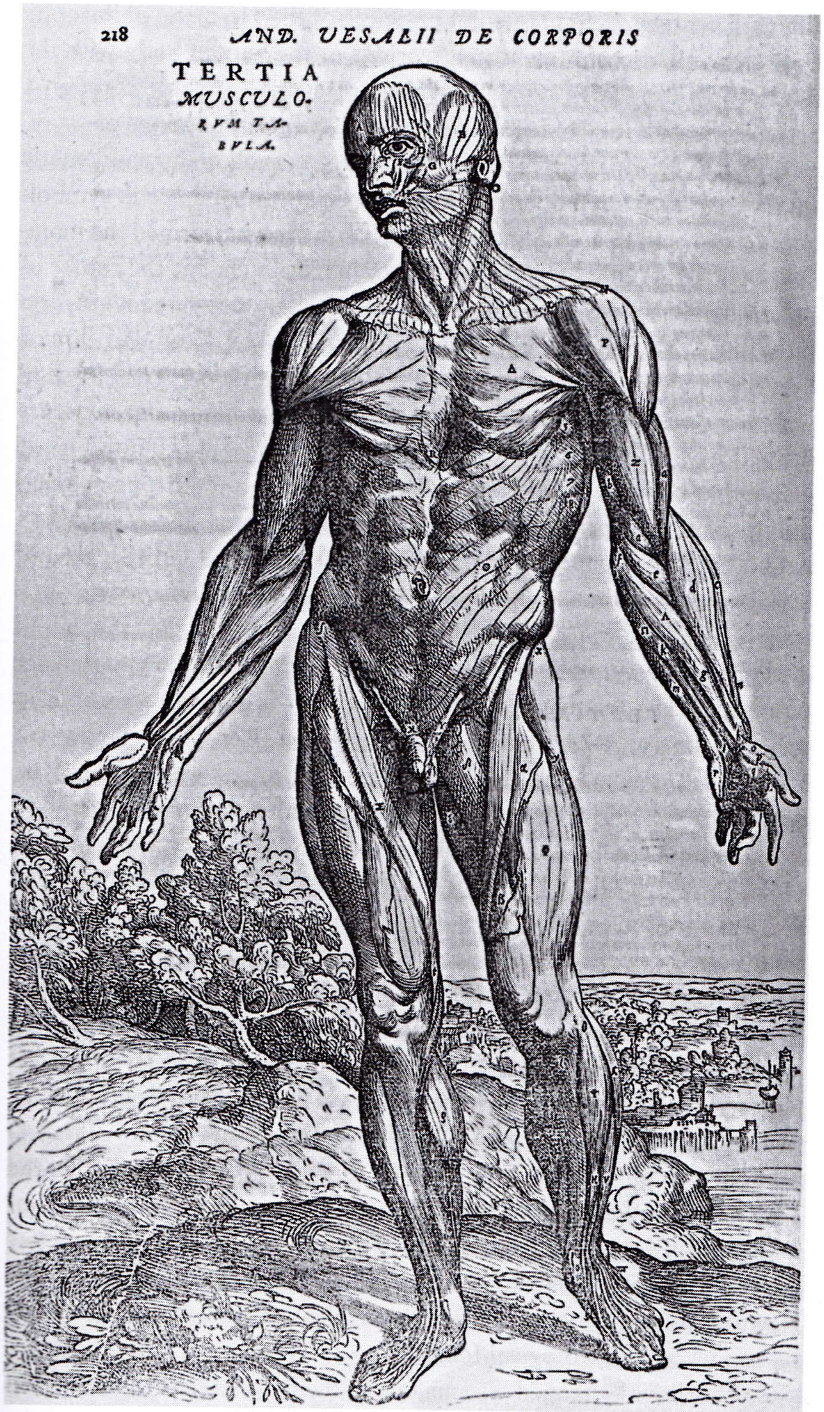


Fig. 11.1. The new anatomy. With the creation of gunpowder weapons, physicians and surgeons were confronted with treating more severe wounds and burns. A military surgeon, Andreas Vesalius, produced the first modern reference manual on human anatomy in 1543, the same year that Copernicus published his book on heliocentric astronomy.

to be seen as an originator of the Scientific Revolution. Widely traveled and a learned man, Paracelsus worked as a military surgeon and then taught for many years at the university in Basel.

The occult sciences gained legitimacy and momentum with the recovery and translation of the so-called Hermetic corpus in the midfifteenth century. A fundamental principle of the Hermetic philosophy linked the microcosm (or "small world") of the human body with the macrocosm (or "large world") of the universe as a whole through a system of occult (or "hidden") correspondences and relations of "sympathy" and "antipathy." The world, therefore, took on an emblematic quality, replete with hidden meanings, associations, and occult symbolism. In addition to astrological beliefs, Hermeticism affirmed the magical power of an enlightened magician or magus to change the course of nature. (The principle of Renaissance magic that postulated a universe pulsating with "forces" the magus could learn to command flowed into the modern notion, enunciated by Newton, of a universal force of gravity.) Hermeticism thus saw a transcendental, divine order in nature framed by underlying mathematical realities, and held the optimistic vision that humans could both understand nature and, through a technology of magic operate upon it in their own interests. These characteristics align Renaissance magic with many of the same individuals and historical forces that gave rise to the Scientific Revolution. The anti-Aristotelian and extra-university nature of these movements should also not be overlooked, nor should the opportunities they invited for patronage. The relative decline of magic later in the seventeenth century and the transition to more "open" systems of knowledge represent a major transition in the Scientific Revolution, but in the meantime Renaissance magic offered allegedly useful and practical powers.

A monumental historical dislocation, the Protestant Reformation *broke the spiritual and political unity of the Catholic Church in the* West in the sixteenth century. The Reformation called into question received religious authority, notably that of the Vatican. In retrospect it represents a major step in the secularization of modern society—that is, the historical shift from ecclesiastical to lay, civil authority governing society. The Reformation began when Martin Luther nailed his Ninety-Five Theses, which were controversial religious propositions, to the door of the church at Wittenberg in 1517, setting off a period of often bloody religious struggle that racked Europe through the Thirty Years' War that ended in 1648. The Scientific Revolution unfolded against the background of the Reformation, and many of its key figures—Johannes Kepler, Galileo Galilei, René Descartes, and Isaac Newton, to name just a few—became deeply affected by religious issues sparked by theological foment.

To this list of changed circumstances facing scientists in the period of the Scientific Revolution, a comparatively minor, yet increasingly irritating problem needs be added: calendar reform. Instituted by Julius Caesar in 45 BCE, the Julian calendar of 365¼ days (with its added full day every fourth February) is longer than the solar year by roughly 10 minutes. By the sixteenth century, the Julian calendar was out of sync with the solar year by some 10 days. Such an inconvenient disjuncture between civil and celestial time exacerbated the already tricky problem of setting the dates for Easter. Pope Sextus IV attempted calendar reform in 1475, but nothing came of it. Pope Leo X raised the issue again in 1512. Consulted on the matter, Nicholas Copernicus expressed his opinion that astronomical theory must be attended to before practical calendar reform was possible.

The Timid Revolutionary

Born in Poland, Copernicus (1473–1543) lived most of his life on the fringes of contemporary scientific civilization, working as a church administrator (canon) in a position gained through family connections. Apparently a timid person, submissive to authority, Copernicus seems an unlikely character to have launched any sort of revolution. In 1491 he matriculated at the University of Cracow, and he spent a decade around 1500 at various universities in Italy, where, in addition to formally studying law and medicine, he developed his interest in astronomy and in general absorbed the cultural ambience of the Italian Renaissance. Indeed, in a typical humanist exercise while still a student, Copernicus translated an otherwise obscure, noncontroversial Greek poet, Theophylactus.

The key to understanding Copernicus and his work comes with the recognition that he was the last of the ancient astronomers, not the first of the moderns. A conservative, he looked backward to ancient Greek astronomy, not forward to some new tradition. He worked as a successor to Ptolemy, not as a precursor of Kepler or Newton. He was at most an ambivalent revolutionary. His object was not to overthrow the old system of Greek astronomy, but rather to restore it to its original purity. In particular, he took seriously the injunction issued nearly 2,000 years earlier to "save the phenomena" and to explain the movements of the heavenly bodies strictly in terms of uniform circular motion. For Copernicus, Ptolemaic astronomy failed to provide a satisfactory account of the stations and retrogradations of the planets; with its elaborate geometrical constructions, it was an astronomical "monster." In particular, he repudiated Ptolemy's equant point—that arbitrary mathematical point in space whence astronomers measured the uniform circular motion of bodies. Uniformity of motion for orbits based on equants was merely a fiction; in fact, as long as astronomers deployed equants, they implied that the planets moved with nonuniform speeds. There had to be a better way, one more consistent with uniform circular motion and ancient tradition.

For Copernicus, that better way turned out to be heliocentrism or placing the sun at (or at least near) the center of the solar system and making the earth a planet. He first proposed heliocentrism in an anonymous manuscript tract, the "Commentariolus," which he circulated among professional astronomers after 1514. But he held off publication of his great work, *De revolutionibus*, possibly because he felt such secrets should not be revealed and certainly for fear, as he put it in his dedication to the pope, of being "hissed off the stage" for such an "absurd" theory. A younger German astronomer and protégé, Rheticus, saw Copernicus's manuscript and published a notice of it, the *Narratio prima* or "First Account," in 1540. With the way apparently cleared, Copernicus approved publication, and his *De revolutionibus orbium coelestium* duly appeared in 1543 just before his death.

Copernicus did not base his astronomy on any new observations. Nor did he *prove* heliocentrism in *De revolutionibus*. Rather, he simply hypothesized heliocentrism and worked out his astronomy from there. In the manner of Euclid's geometry Copernicus posited heliocentrism in a handful of axioms and developed propositions concerning planetary motion under the assumed conditions. He made these bold assumptions for essentially aesthetic and ideological reasons. For Copernicus the heliocentric system possessed greater simplicity and harmony in its proportions; it was intellectually more refined—more "pleasing to the mind"—and economical than what he regarded as the inelegant system of Ptolemy.

The greater simplicity of heliocentrism lay primarily in how it explained the stations and retrogradations of the planets which remained so awkward to explain in geocentric accounts. In the Copernican system such motion is an illusion resulting from the relative motion of the earth and the planet in question against the background of the fixed stars. That is, from a moving earth a moving planet may appear to stop, move backward, and then move forward again, while actually both the observed and the observer circle the sun without any backward motion. With heliocentrism the appearance of the stations and retrogradations of the planets remains, but the problem vanishes: "retrograde" motion automatically follows from the postulate of heliocentrism. The revolutionary character of Copernicus's achievement is nowhere more evident than in the fact that with the adoption of heliocentrism the central theoretical problem in astronomy for two millennia simply disappears.

The Copernican hypothesis was simpler and aesthetically more appealing on additional grounds. It explained why Mercury and Venus never stray farther from the sun than an angular distance of 28° and 48°, respectively. The Ptolemaic system adopted an ad hoc, unsatisfying solution to the problem, while for Copernicus, because the orbits of Mercury and Venus fall within the orbit of the earth, those planets must remain visually in the vicinity of the sun. Similarly the Copernican system dictated a definite order to the planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn), while the matter remained uncertain in Ptolemaic astronomy. Using the Copernican planetary order, observed planetary positions, and simple geometry, astronomers could calculate the relative distance of planets from the sun and the relative size of the solar system.

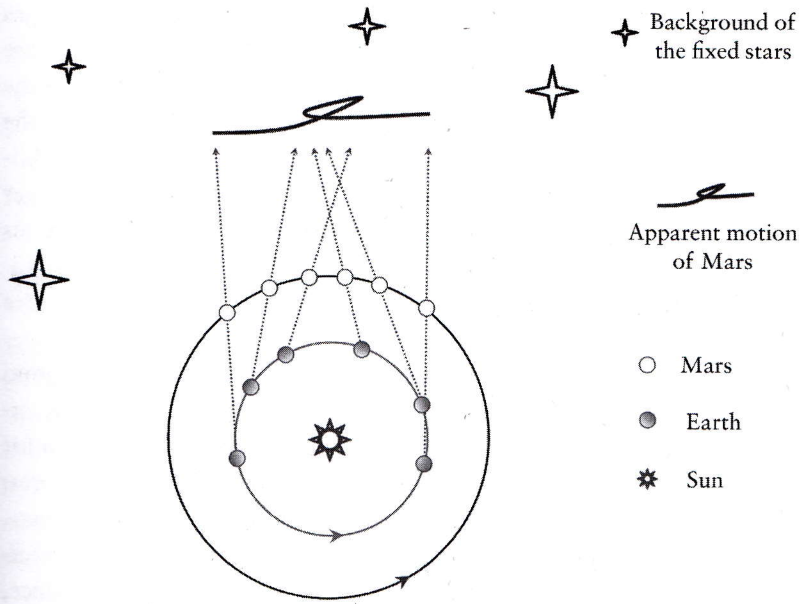


Fig. 11.2. Retrogradation of the planets in the heliocentric system. Copernicus provided a simple explanation for the age-old problem of stations and retrogradations of the planets. In the heliocentric system a planet's looping motion as seen against the background of the fixed stars is only apparent, the result of the relative motion of the earth and the planet in question (the superior planet Mars in this case).

For Copernicus and like-minded astronomers, the sun occupied a position of paramount importance. In an oft-quoted passage in *De revolutionibus*, one redolent of Neoplatonism if not actual sun-worship, Copernicus wrote:

> In the middle of all sits the Sun enthroned. In this most beautiful temple could we place this luminary in any better position from which he can illuminate the whole at once? He is rightly called the Lamp, the Mind, the Ruler of the Universe; Hermes Trismegistus names him the Visible God, Sophocles' Electra calls him the All-seeing. So the Sun sits as upon a royal throne ruling his children the planets which circle round him . . . Meanwhile the Earth conceives by the Sun, and becomes pregnant with an annual rebirth.

For Copernicus the earth rotates once a day on its axis, thus accounting for the apparent daily motion of everything in the heavens, and the earth revolves around the sun once a year, accounting for the sun's apparent annual motion through the heavens. But Copernicus ascribed not two, but three motions to the earth, and to understand Copernicus's "third motion" reveals the essence of his worldview. In a word, Copernicus held that the planets orbit the sun not in empty or free space but embedded in the crystalline spheres of traditional astronomy. Thus, the spheres in the title of his magnum opus, *On the Revolution of the Heavenly Spheres*, refer not to the spheres of the planets—Earth, Mars, Venus, and so on—but to the crystalline spheres that carry the planets!

That being the case, a serious problem arose for Copernicus, for if the earth were carried around the sun in a solid crystalline sphere, the earth's north-south axis would not maintain its constant "tilt" of

23½ degrees toward the pole star (Polaris), and therefore no changes in seasons would occur. Introducing another "conical" motion of the earth's axis, Copernicus kept the earth pointed to the same spot in the heavens and thus accounted for seasonal changes while having the earth carried around by its celestial sphere. (See figure 11.3.) In addition, by making this annual third motion of the earth slightly longer than the annual period of the earth's orbit of the sun, Copernicus explained yet another tricky phenomenon, the precession of the equinoxes or the separate motion of the sphere of the fixed stars over a 26,000-year period.

Of course, like Aristarchus before him, Copernicus had to respond to the traditional objections to the idea of a moving earth, and he offered a modified version of standard Aristotelian physics to account for the phenomena. For Copernicus, circular motion is natural to spheres; therefore the earth rotates by its very nature and, like the other planets, is carried around the sun by the inherent natural motion of its crystalline sphere. Material particles naturally aggregate into spheres; hence, objects fall downwards on earth, not to the center of the universe, but only to the center of the earth. Bodies do not fly off the earth, given its diurnal and annual motions, because they share in the circular motions of their "mother." Qualitatively, it all works wonderfully well, and the aesthetic superiority shines through in the first twelve folios (twenty-four pages) of the first book of *De revolutionibus*, wherein Copernicus presents the general outline of his system.

The other five books and 195 folios of *De revolutionibus* are quite a different matter. There one finds a highly technical reform of mathematical astronomy, as rigorous and abstruse as Ptolemy's *Almagest*. In fact, superficial comparison can hardly distinguish the works. Copernicus did not intend his work for popular consumption, wanting only

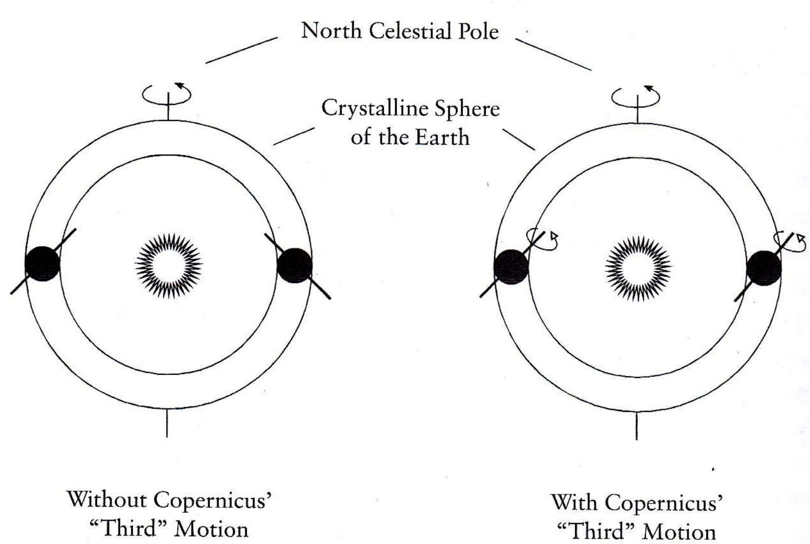


Fig. 11.3. Copernicus's third ("conical") motion of the earth. To account for the fact that the earth's axis always points in the same direction, Copernicus added a third motion for the earth in addition to its daily and annual movements.

to be judged by other professional astronomers. Indeed, he said of his audience that "mathematics is written for mathematicians," and verso to his title page he had printed Plato's motto, "Let no one ignorant of geometry enter here."

Considered as a technical treatise for professional astronomers, therefore, *De revolutionibus* loses much of its aesthetic appeal. As it turns out, the sun stands only near the center of the solar system, not at the center. Copernicus avoided the dreaded equant, to be sure, but, committed to circular motion, he was forced to retain an elaborate apparatus of epicycles and eccentrics in order to explain the remaining irregularities in the apparent speed of the planets as they circled the sun. In the final analysis, as the technical details piled up, Copernicus's astronomy was not any more accurate or more simple than Ptolemy's. Although he eliminated large epicycles, depending on which circles one counts, Copernicus may have actually employed more epicycles than the corresponding contemporary version of Ptolemy.

Copernican astronomy also faced several nettlesome technical problems that undermined its appeal considerably. The most serious was the problem of stellar parallax, the same problem that subverted Aristarchus and heliocentrism in Greek antiquity. As noted in discussing Aristarchus's proposal, as the earth revolves around the sun, the stars ought to change their apparent relative positions. But astronomers observed no such stellar parallax.

The phenomenon of stellar parallax is in fact a very subtle one, never observable in naked-eye astronomy and not actually demonstrated until 1838. The discovery of stellar aberration by the English Astronomer Royal, James Bradley, in 1729 demonstrated the earth's annual motion but, amazingly, only in 1851 did the physicist J.-B.-L. Foucault definitively prove the daily rotation of the earth by using a giant pendulum. By the eighteenth and nineteenth centuries Ptolemaic astronomy had all but ceased to exist; by that time astronomers universally held to the earth's diurnal motion and to heliocentrism. Can it be that such definitive proofs are not what is needed to persuade converts to a new science?

Be that as it may, the Copernican explanation for the lack of observed stellar parallax resembled Aristarchus's: he assumed the stars were very far away and hence the parallax remains too small to be observed. But this hypothesis produced further problems, notably that the size of the universe ballooned to incredible proportions and the size of the stars (extrapolating from their apparent size) likewise became unbelievably immense. Ptolemaic astronomy had set the sphere of fixed stars at a distance of 20,000 Earth radii. For Copernicus the stars had to lie at least 400,000 Earth radii away, an apparently absurd distance in the context of sixteenth-century astronomy.

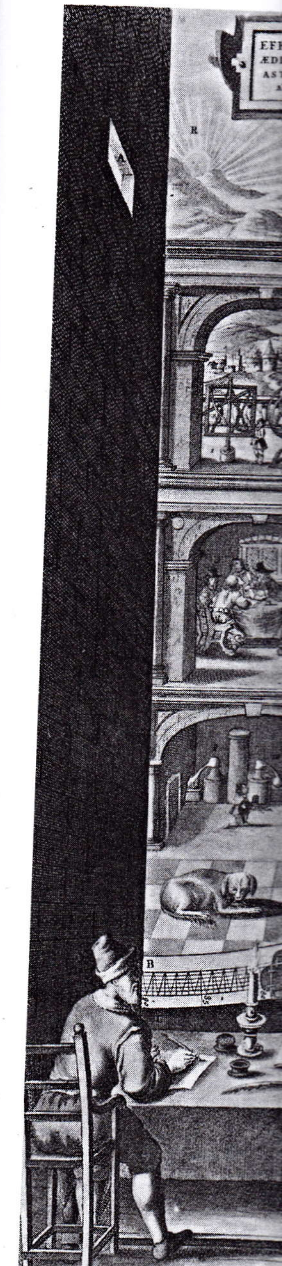
The fact that falling bodies do not appear to be left behind as the earth allegedly moves was also a strong impediment to the acceptance of heliocentrism. These and other technical problems meant that Copernican heliocentrism was not immediately hailed as a self-evidently correct or superior astronomical system. But other issues loomed, too, including religious objections that heliocentrism seemingly contradicted passages in the Bible. Copernicus dedicated *De revolutionibus* to Pope Paul III, perhaps to stave off such objections. Pope Clement VII had earlier learned of Copernicus's views in the 1530s and did not object, and Catholic astronomers and churchmen did not take theological exception to the Copernican hypothesis in the second half of the sixteenth century. Some leading Protestants, on the other hand, including Luther and the Danish astronomer Tycho Brahe, did pose such objections, but only in the next century when Galileo fanned the flames of theological controversy did they flare up against Copernicanism.

A spurious prefatory letter attached to *De revolutionibus* explains why Copernicanism did not provoke more strenuous theological reactions. A Lutheran cleric, Andreas Osiander, saw Copernicus's book through the press and on his own authority added an anonymous foreword, "To the Reader Concerning the Hypotheses of this Work." Osiander-cum-Copernicus wrote that heliocentrism need not be true or even probable, merely that it provides a convenient mathematical device that permits astronomers to make more accurate calculations. Copernicus himself held heliocentrism to be a true description of the physical world, but based on Osiander's preface he was taken merely to have created a useful fiction. Paradoxically, Osiander qua Copernicus may have helped pave the way for acceptance of Copernicanism by making it superficially palatable for all concerned.

The idea of heliocentrism slowly diffused among astronomers after Copernicus. A new set of astronomical tables—the so-called Prutenic Tables calculated on Copernican principles by the astronomer Erasmus Reinhold and published in 1551—represents one practical result forthcoming from Copernicus's work. In 1582, based on these new tables, authorities finally effected calendar reform by instituting the Gregorian calendar in use today. (Named after Pope Gregory XIII, the Gregorian calendar suppresses leap years for centennial years, except those divisible by four.) By the same token, although Copernicus's book was reprinted in 1566 and again in 1617, only a handful of technical astronomers ever read him. A revolution in astronomy is barely discernible even in the second half of the sixteenth century. Not an abrupt transformation of contemporary astronomy or of worldview, the Copernican revolution was, at most, a revolution by degrees.

Tycho's Turn

The great Danish astronomer Tycho Brahe (1546–1601) added to the momentum of the revolution Copernicus had quietly begun. A haughty and arrogant aristocrat, for 20 years from the mid-1570s to the mid-



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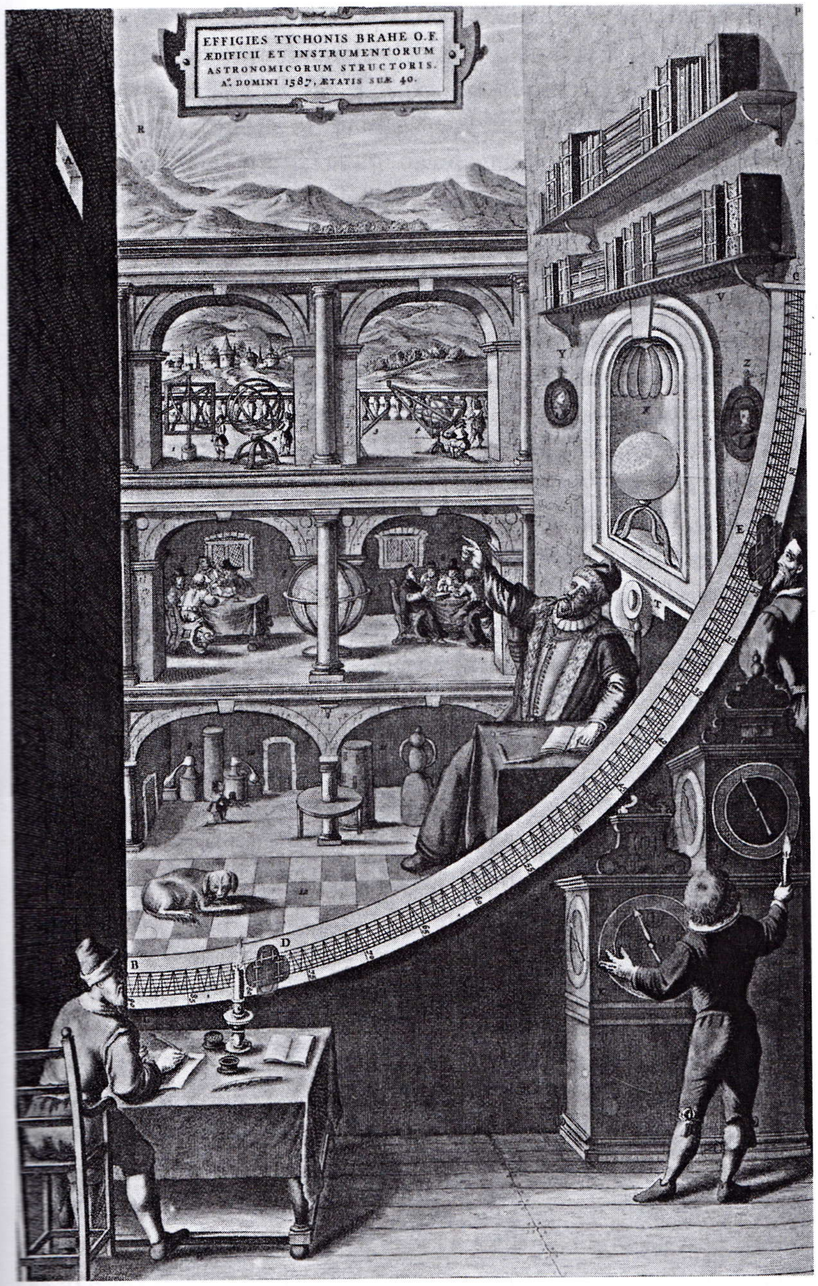


Fig. 11.4. Tycho Brahe and the mural quadrant. The remarkably accurate set of naked-eye astronomical observations compiled by the sixteenth-century Danish astronomer Tycho Brahe and his assistants depended on large instruments, such as the mural quadrant depicted here. This famous engraving also shows the other components of the research installations erected by Tycho, including an alchemical lab. No contemporary university or university professorship could have paid for Tycho's activities. He depended on major subsidies from the Danish crown.

1590s Tycho ruled over the Danish island of Hveen given to him as a fief by the Danish king Frederick II, along with its village, farms, and peasants. There he built and equipped two great astronomical palaces—Uraniborg, the castle of the heavens, and Stjerneborg, the castle of the stars—which together comprised the most magnificent scientific installation of its day. Tycho added his own printing press, a paper mill, a library, and several alchemical laboratories. A practicing alchemist and astrologer, he cast horoscopes for patrons and friends and gave away alchemical medicines. Having lost part of his nose in a duel, Tycho sported a prosthetic replacement, and with his own jester, pets, and coteries of assistants the lord of Uraniborg may seem a virtual self-parody of a Renaissance magus. Tycho had a falling-out with a succeeding Danish king and left Denmark in 1597 to take up a court position as Imperial Mathematician to the Holy Roman Emperor, Rudolph II, in Prague. Kepler reports that Tycho died from a burst bladder from having drunk too much at the banquet table and being too polite to get up to relieve himself.

But Tycho was not merely an eccentric. He was also an adept astronomer who understood the needs of his science. Early in his career he became convinced that the perfection of astronomy depended on accurate and sustained observations of the heavens, and he made it his life's work to undertake those observations. To that end he built large and delicately calibrated naked-eye instruments, such as mural quadrants and armillary spheres—some twenty major instruments at Uraniborg and Stjeneborg. Indicative of the "big science" nature of his enterprise, Tycho received government support totaling some 1 percent of crown revenues, and he boasted that many of his instruments individually cost more than the annual salary of the highest-paid university professors. (Like Copernicus, Tycho's career developed outside the university.) Using these huge and expensive instruments, shielding them from wind stress, minimizing temperature variations, testing and correction for their intrinsic errors, and adjusting for atmospheric refraction, Tycho produced the most precise naked-eye observations ever, trustworthy down to five or ten seconds of arc in some cases, a minute or two in others, and four minutes of arch in all cases. (A minute of arc is 1/60 of a degree; a second of arc is 1/60 of an arc minute; and, of course, 360° span a circle.) This margin represents an exactitude double that of ancient astronomical observations and one not bested by telescopic observations for yet another century. But the beauty of Tycho's data derived not only from their intrinsic accuracy, but from the systematic character of the observations that Tycho and his assistants methodically compiled night after night over an extended period of years.

Two celestial events further shaped Tycho's astronomy. On the evening of November 11, 1572, as he left his alchemical laboratory, Tycho noticed a "new star" blazing as brightly as Venus in the constellation of Cassiopeia. He wrote about this "stella nova" giving rise to our term nova or supernova, meaning an exploding star. The nova in question shone for three months, and by executing exact parallax observations, Tycho showed that the new star was not located in the earth's atmosphere or in the region below the moon, but stood in the heavens above the sphere of Saturn. In other words, the "new star" really was a new star, even if a temporary one. Tycho thus demonstrated the mutability of the heavens and thereby issued a strong challenge to a central tenet of received dogma in Western cosmology.

Tycho's observations of the comet of 1577 likewise proved unsettling to traditional astronomical theory. Again based on parallax observations, Tycho showed not only that the comet moved in the regions above the moon, but he raised the possibility that it also cut through the crystalline spheres supposedly carrying the planets. In other words, the celestial spheres—those mainstays of Western cosmology and celestial dynamics from at least the fourth century BCE—were not real. After Tycho, the only spheres in the heavens were the observed spherical bodies of the sun, the moon, the earth, and the other planets.

Although his work challenged received doctrines, Tycho rejected Copernicus and heliocentrism on strong empirical grounds, especially the lack of observable stellar parallax and because of the consequence that in Tycho's calculations, given the heliocentric system, the fixed stars had to lie an inconceivable 7,850,000 Earth radii distant from the center. The daily or diurnal motion of the earth in the heliocentric system also seemed absurd, and, indicative of a new imagery stemming from the Military Revolution, Tycho introduced a new argument against a spinning earth: a cannon fired toward the west (and a rising horizon) ought to outdistance shots fired toward the east (and a sinking horizon), altogether against experience. Then, too, Tycho, a Protestant, voiced religious objections to the heliocentric system.

In response to deep problems affecting both Ptolemaic and Copernican astronomy Tycho proposed his own system in 1588. In the Tychonic geoheliocentric system the earth remains quiescent at the center of the cosmos, the planets revolve around the sun, and the sun revolves around the earth. This system possessed several advantages: it accounted for stations and retrogradations of the planets without using epicycles, it removed the absurdities of a moving earth, it maintained the traditional scale of the universe, it eliminated the crystalline spheres, and it was mathematically as accurate as its competitors. Holding the earth at rest, the Tychonic system was the equivalent of the Copernican system without the disadvantages of the latter. The Tychonic system represents good, even if conservative, science. But by 1600 with three competing systems and research programs in existence—Ptolemaic, Copernican, and Tychonic—a crisis in astronomy began to mount.

The Music of the Spheres

The case of Johannes Kepler (1571–1630) belies the notion that the internal logic of scientific discovery alone suffices to account for scientific change. Early in his intellectual career Kepler became obsessed with astrology and number mysticism, and more than anything else these obsessions drove his work, shaped his scientific accomplishments, and redirected the course of the Scientific Revolution. Coming from an impoverished and dysfunctional family—his father an errant soldier

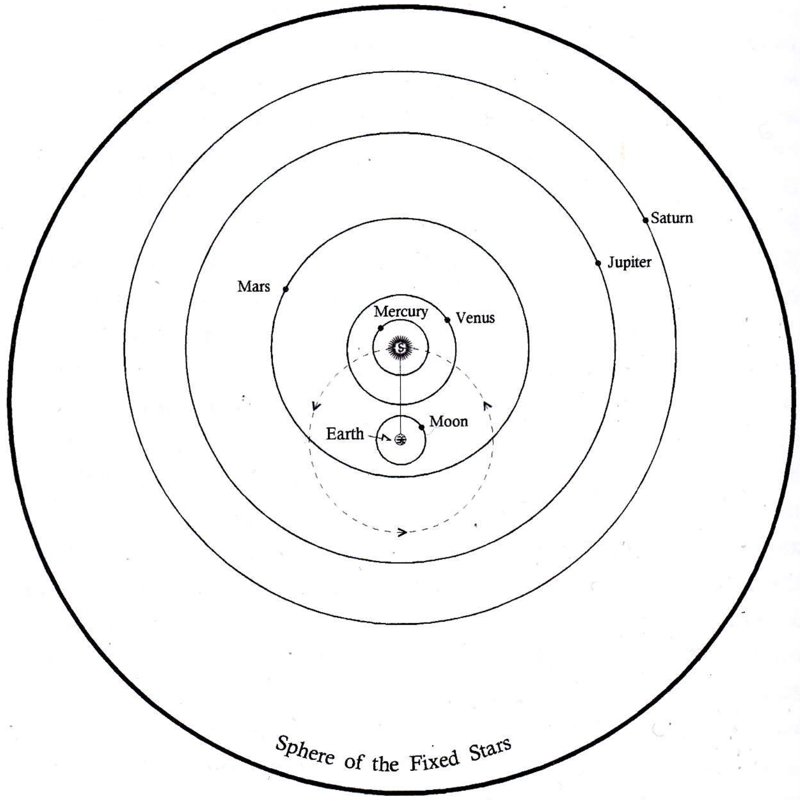
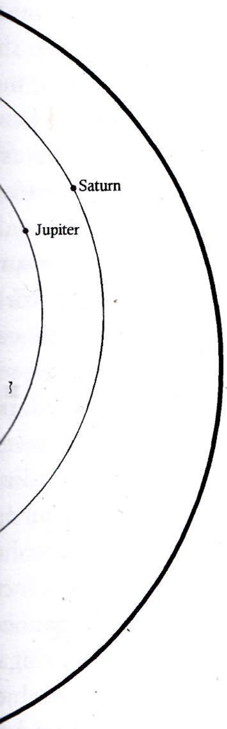


Fig. 11.5. The Tychonic system. In the model of the cosmos articulated by Tycho Brahe in 1588, the earth remains stationary at the center of the universe. The sun orbits the earth, while the other planets revolve around the sun. Tycho's system was good science in that it solved a number of difficult problems in contemporary astronomy, but it did not receive wide acceptance.

of fortune, his mother later in life tried as a witch—Kepler attended Lutheran schools and the university at Tübingen as a talented scholarship boy. An unhappy person with bad eyesight and a number of other physical afflictions, Kepler compared himself to a mangy dog. Although he disdained some aspects of astrology, he saw it as an ancient and valid science, and throughout his life he cast horoscopes and wrote up prognostications and calendars (like farmers' almanacs), from which he earned a regular income. On first learning of the Copernican system he became a convert, finding it, like Copernicus did, "pleasing to the mind" and revealing of the workings of the divine in nature.

Kepler did not set out to become an astronomer, but pursued higher studies in theology. However, before granting his degree, authorities at Tübingen nominated Kepler to fill a position as provincial calendar maker and teacher of mathematics in the Protestant high school at Graz in Austria, and Kepler accepted. He was a poor teacher, with so few math students that the school assigned him to teach history and ethics. One day—he tells us it was July 19, 1595, in front of his presumably bored geometry class—Kepler had a revelation. He was discussing the cube, the tetrahedron, the octahedron, the icosahedron, and the dodecahedron, which are the five regular solids with identical



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faces and angles between the faces. (The Greeks had proven that there cannot be more than these five.) Kepler's mystical insight consisted in imagining that these solids might somehow frame the universe, that is, establish the mathematical proportions that spaced the planetary orbits outward from the sun. Thus inspired, Kepler developed his views on the geometrical structure of the universe in a book, *Mysterium cosmographicum* (*The Mystery of the Universe*), that appeared in 1596. Kepler's *Mysterium* was the first overtly Copernican work since *De revolutionibus* more than a half a century before, and its origin in pedagogy is one of a handful of exceptions proving the historical rule that nothing of importance for science ever happens in classrooms.

Psychically driven to unpack divine mathematical harmonies of the universe, Kepler was physically driven from Graz in 1600 by the Catholic counter-Reformation and his refusal to convert to Catholicism. He managed to find his way to Prague and a position as Tycho's assistant for the last two years of Tycho's life. The noble, aging Dane assigned the pitiable, younger Kepler data for the planet Mars, in the hope that Kepler could reconcile Tycho's extraordinarily accurate ob-

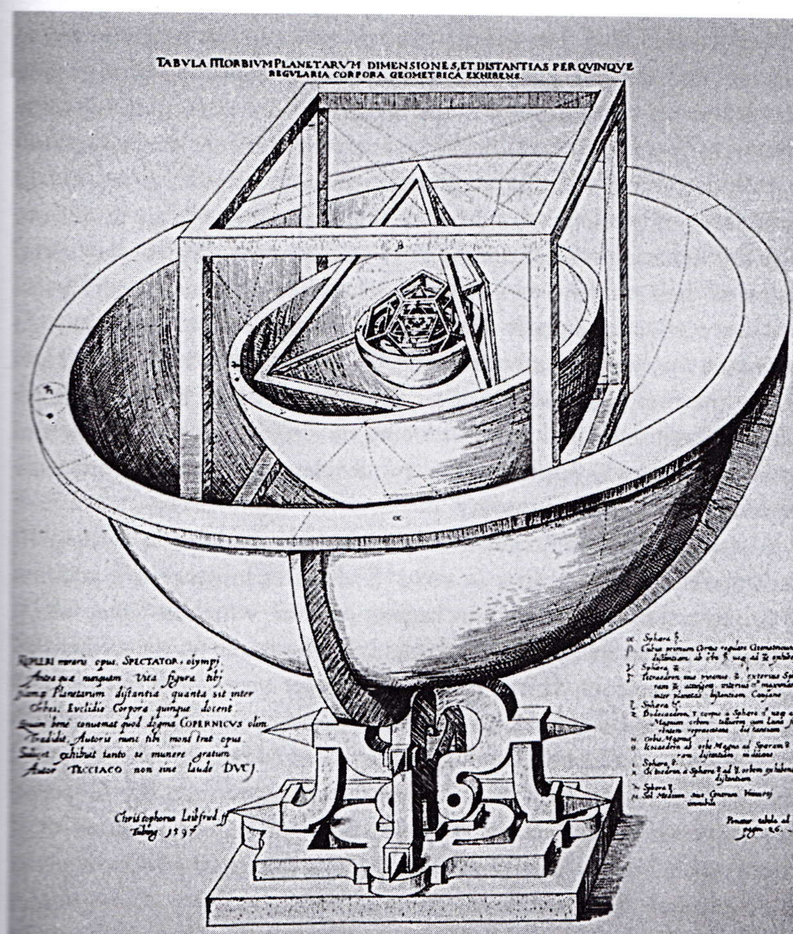

Fig. 11.6. The mystery of the cosmos. In his *Mysterium cosmographicum* (1596) Johannes Kepler conjectured that the spacing of the six known planetary orbits could be explained by nesting them in and around the five regular solids.

servations with Tychonic theory. The choice of Mars was fortuitous, in that the orbit of Mars is the most eccentric, or noncircular and off-centered, of all the planets. Kepler took up the problem with a vengeance, but only to rescue Mars for Copernican theory and his own intuitions of celestial harmonies. In an intellectual struggle of epic proportions, Kepler worked fervently on the problem for six years, leaving behind some 900 manuscript pages of calculations, testimony to a heroic endeavor and the fact that this exercise in curve fitting proceeded without benefit of mechanical or electronic calculators. In his published account Kepler leads his reader through every tortuous twist and turn. At one point, his circular model for Mars matched the observational data to within 8 minutes of arc, a tremendous achievement, but knowing that Tycho's data were good to 4 minutes, Kepler had to reject his own accomplishment. He made mistakes in his calculations, and then made other mistakes that corrected for them. He got the "right" answer and failed to see it. Then, on recognizing an obscure mathematical connection concerning the secant of an angle, Kepler had another flash of insight. "It seemed as if I awoke from sleep and saw a new light break on me," he wrote, and indeed he awoke in a new world.

Kepler concluded that the planets orbit the sun not in circles but in ellipses. This discovery, of course, marks an astonishing turn, in that circles had provided a physics and a metaphysics governing heavenly motion at least since Plato nearly 2,000 years earlier. In his *Astronomia Nova* of 1609 Kepler enunciated the first two of his celebrated three laws of planetary motion: 1) that the planets orbit in ellipses with the sun at one focus, and 2) in what amounts to a planetary speed law, that their radii sweep out equal areas in equal times. Kepler's second law carries the equally disturbing consequence that the planets do not move *uniformly*. As it turns out, Kepler developed his second law before the first, and himself never drew attention to his laws per se. Nevertheless, with the planets moving as Kepler described them and with the sun now indisputably central, Kepler's *Astronomia nova* truly represented a "new astronomy."

Kepler remained in Prague as Imperial Mathematician to Rudolph II until the latter's abdication in 1612. Thereafter he secured a position as provincial mathematician in Linz in Austria, which lasted to 1626, when he moved on to Ulm and Sagan. In the latter period of his life, while the disastrous Thirty Years' War swept over Germany and disrupted his very existence on more than one occasion, Kepler wrote an *Epitome of Copernican Astronomy* (1618–21), which presented his own elliptical vision of the solar system more than the Copernican one, and the *Rudolphine Tables*, a new and highly accurate set of astronomical tables based both on Tycho's data and on Copernican/Keplerian heliocentrism.

In 1619 Kepler issued his *Harmonice mundi*, or *Harmonies of the*

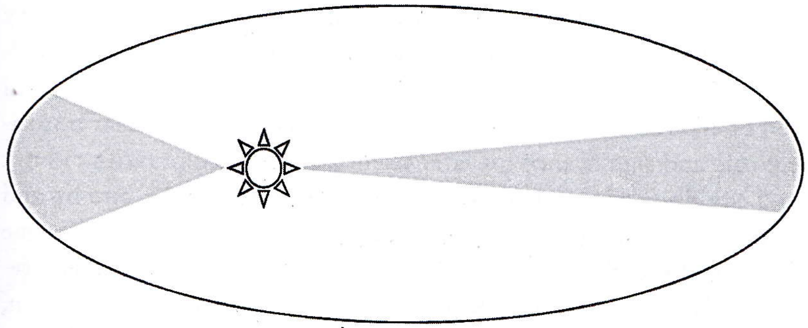

Fig. 11.7. Kepler's elliptical motion of the planets. Based on Tycho Brahe's data, Johannes Kepler broke with the age-old notion that the heavenly bodies move in circles. Kepler reformulated planetary motion in what came to be known as Kepler's three laws: (1) the planets orbit the sun in ellipses with the sun at one focus; (2) planets sweep out equal areas in equal times; and (3) the square of the time of an orbit equals the cube of the mean distance from the sun, or $t^2 \propto r^3$. Kepler reached these conclusions entirely on the basis of astronomical observations and geometrical modeling without providing a convincing physical explanation for why the planets move as they do.

World. This work culminated the effort that began with the *Mysterium cosmographicum* and Kepler's meditations and researches on the mathematical order underlying the structure of the cosmos. In the *Harmonice mundi* Kepler calculated astrological relations, correspondences of planets with metals, the music of the spheres—those unheard tones that he believed were generated by the planets in their motions—and like connections. Buried in this work lay Kepler's third law, that the square of the time of a planet's orbit is proportional to the cube of the mean radius—$t^2 \propto r^3$—at the time an oddly empirical law.

Astronomers and physicists preceding Kepler—even those few who held to heliocentrism—possessed a traditional dynamics for heavenly motion: the planets were understood to move uniformly in circles by their innate natures or carried by crystalline shells. But having dispensed with uniform circular motion, Kepler faced the problem of providing a dynamics and explaining why the planets move the way they do through space. Kepler was aware of this obligation and subtitled his *Nova Astronomia* of 1609 *The New Astronomy, Based on Causes, or Celestial Physics*. At an early stage Kepler believed that the sun possessed an *anima motrix*, a moving soul or spirit akin to the Holy Ghost, that propelled the planets through their courses. In his more mature formulations he substituted for this animate spirit a more inanimate moving force or *vis motrix*, a kind of magnetic power. Kepler derived this latter notion from William Gilbert's influential *De Magnete*, published in 1600, which showed the earth to be a huge magnet. For Kepler, then, the planets deviate from circular motion as the sun's and the planets' magnets alternately attract and repel. Kepler's celestial physics provided a plausible explanation for planetary motion, but not a compelling one, for problems remained. For example, Kepler does not explain how the force emanating from the sun acts tangentially, that is, how it "sweeps" the planets along, something like a broom, and can act at right angles to lines of force emanating from the sun. Also, paradoxically, he never treats this motive power with the same mathematical rigor and precision he used in determining the orbits of planets. After Kepler, the dynamics of heavenly motion remained an open question.

Kepler died of a fever in 1630 while traveling to petition for money owed him. Although he contributed to it mightily, Kepler did not culminate the Scientific Revolution. We extract Kepler's three laws all too easily from the corpus of his work because we know their historical role and significance for later science, but contemporaries did not and could not. Few astronomers actually read his works, and by and large Kepler did not win converts. Indeed, most scientists who became aware of Kepler's work, notably his great contemporary, Galileo, rejected his views. As an eccentric mystic, Kepler enjoyed the reputation, rather, of a great astronomer gone slightly mad.