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978-0-521-29295-5 - The Construction of Modern Science: Mechanisms and Mechanics
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Introduction

TWO MAJOR THEMES dominated the scientific revolution of the 17th century—the Platonic-Pythagorean tradition, which looked on nature in geometric terms, convinced that the cosmos was constructed according to the principles of mathematical order, and the mechanical philosophy, which conceived of nature as a huge machine and sought to explain the hidden mechanisms behind phenomena. This book explores the founding of modern science under the combined influence of the two dominant trends. The two did not always mesh harmoniously. The Pythagorean tradition approached phenomena in terms of order and was satisfied to discover an exact mathematical description, which it understood as an expression of the ultimate structure of the universe. The mechanical philosophy, in contrast, concerned itself with the causation of individual phenomena. The Cartesians at least were committed to the proposition that nature is transparent to human reason, and mechanical philosophers in general endeavored to eliminate every vestige of obscurity from natural philosophy and to demonstrate that natural phenomena are caused by invisible mechanisms entirely similar to the mechanisms familiar in everyday life. Pursuing different goals, the two movements of thought tended to conflict with each other, and more than the obviously mathematical sciences were affected. Since they proposed conflicting ideals of science and differing methods of procedure, sciences as far removed from the Pythagorean tradition of geometrization as chemistry and the life sciences were influenced by the conflict. The explication of mechanical causation frequently stood athwart the path that led toward exact description, and the full fruition of the scientific revolution required a resolution of the tension between the two dominant trends.

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The scientific revolution was more than a reconstruction of the categories of thought about nature. It was a sociological phenomenon as well, both expressing the ever increasing numbers engaged in the activity of scientific research and spawning a new set of institutions that have played a more and more influential role in modern life. In my opinion, however, the development of ideas following their own internal logic was the central element in the foundation of modern science and, although I have attempted to indicate something of the sociological ramifications of the scientific movement, this book expresses my conviction that the history of the scientific revolution must concentrate first of all on the history of ideas.

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CHAPTER I

Celestial Dynamics and Terrestrial Mechanics

WHEN THE 17TH CENTURY dawned, the Copernican revolution in astronomy was over fifty years old. Perhaps one should say rather that Copernicus' book, *De revolutionibus orbium coelestium** (1543), was over fifty years old. Whether the book would initiate a revolution had yet to be determined, and two men who had scarcely passed the thresholds of their scientific careers in 1600 were to be the primary agents in assuring that it would. Both Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642) acknowledged Copernicus as their master; both devoted their careers to confirming the revolution in astronomical theory he had begun. To its confirmation each made an essential contribution, though in his contribution each modified Copernicanism in a way the master might not have accepted. Copernicus himself had proposed a limited reformation of planetary theory within the broad outlines of the accepted framework of Aristotelian science. By the time Kepler and Galileo were done, the limited reformation had become a radical revolution, and the work of the 17th century, which laid the foundation for the structure of modern science, consisted in pursuing the questions that Kepler and Galileo opened. Intellectual history does not always divide neatly into packages that fit the calendar, and scientists have not concerned themselves to group their labors into units convenient to the academic curriculum. The dawn of the 17th century, however, did coincide with the dawn of a new era in science.

Kepler had made his professional debut four years earlier with the publication of *Mysterium Cosmographicum** in 1596. To 20th century

* *On the Revolutions of the Heavenly Spheres.*
* *Cosmographic Mystery.*

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eyes, the book appears even more mysterious than the title promises; but when it is probed, its mystery illuminates much of Kepler's work. Avowedly Copernican, the book set out to demonstrate the validity of the heliocentric theory from the number of planets. Because the moon was considered a planet in the Ptolemaic system, the Copernican system had one less planet, six instead of seven. Kepler undertook to demonstrate why God had chosen to create a universe with six planets, that is, a heliocentric universe. God's choice, as it turned out, had been dictated by the existence of five, and only five, regular solids. If a cube were inscribed inside the sphere defined by the radius of Saturn, the radius of the sphere inscribed inside the cube would be that of Jupiter, and so on. The five regular solids define the spaces between six spheres, and because only five regular solids exist, only six planets exist. The question *Mysterium Cosmographicum* asked is not the sort that modern science has tended to pose. Just for that reason, it reveals more clearly the fundamental assumptions with which Kepler approached his work in astronomy. Like Copernicus before him, Kepler had drunk deeply at the spring of Renaissance neoplatonism, and imbibed its principle that the universe is constructed according to geometric principles. Coming two generations later, Kepler had the perspective to see where Copernicus' system failed to achieve the ideal of geometrical simplicity which both of them shared. Kepler's work would be the perfection of Copernican astronomy according to neoplatonic principles.

Kepler was equally convinced that astronomical theory must be more than a set of mathematical devices to account for observed phenomena. It must rest on sound physical principles as well, deriving the motions of planets from the causes producing them. To his greatest work he gave the title *New Astronomy Founded on Causes, or Celestial Physics Expounded in a Commentary on the Movements of Mars.** Since the time of Aristotle, nearly two thousand years before Kepler, there had been virtual unanimity that, physically speaking, the heavens were constructed of crystalline spheres. The perfection and immutability ascribed to the celestial realm required a material different from the four elements that composed the corruptible bodies of the mundane world, and the axial rotation of the spheres, the one movement allowed to the heavens, corresponded to the perfect circular motion from which astronomers were expected to construct their theories. The "Celestial Spheres"

* In the original Latin (and Greek): *Astronomia nova* ΑΙΤΙΟΛΟΓΗΤΟΣ *seu physica coelestis tradita commentariis de motibus stellae Martis.*

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referred to in Copernicus' title were the same crystalline spheres. Kepler, however, was convinced that crystalline spheres do not exist. Careful observations by Tycho Brahe and others of the new star of 1572 and of the comet of 1577 had demonstrated that both were located in the realm beyond the moon, which was claimed to be immutable. The motion of the comet appeared to be incompatible with the existence of crystalline spheres. "There are no solid spheres as Tycho Brahe has demonstrated"—the phrase runs like a refrain through Kepler's works. And if the crystalline spheres had been shattered, a new celestial physics must be established to account for the stable, recurring motions of the planets. The constant search for physical causes went hand in hand with the search for geometrical structure—to Kepler, the two were only different aspects of a single reality.

The physical principles he employed expressed the basic propositions of Aristotelian dynamics, and the 17th century replaced them with a wholly different set. Nevertheless, Kepler was the founder of modern celestial mechanics. He was the first to insist categorically that the long-accepted crystalline structure of the heavens did not exist and that a new set of questions about celestial motions had to be formulated. Convinced of the uniformity of nature, he attempted to account for the phenomena by the same principles employed in terrestrial mechanics. More than anything else, this aspect of Kepler's thought makes him a revealing figure in the early history of modern science. In him we can observe a celestial mechanics, founded on the principles of terrestrial mechanics, begin to replace the purely kinematic treatment of the heavens. An astronomy that sought to comprehend the forces controlling planetary motions supplanted the manipulation of circles that were deemed to express the perfection and incorruptibility of a realm apart. If Kepler's dynamic principles ultimately revealed themselves to be unsatisfactory, he followed them, nevertheless, to the laws of planetary motion that are accepted today.

It was, of course, the real mathematical structure and the real physical causes which Kepler sought to uncover. Such must square with the observations, and Kepler refused to force a priori theories onto nature in violence of the observed facts. Here lay the problem of the *Mysterium Cosmographicum*. In the cases of Mercury and Saturn, the theory diverged widely from the accepted observations. Kepler was aware, however, that the accepted observations were unreliable, and that a contemporary observer, Tycho Brahe, was collecting a body of data more accurate by far. In 1600, Kepler became Tycho's assistant. In 1601,

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Tycho died; and with no right whatever beyond the prerogative of genius, Kepler simply appropriated the precious body of observations. They served as the irreplaceable data on which his genius worked to develop the laws of planetary motion.

Mars was to be the principal object of his labor. Kepler, who always asserted the structural unity of the solar system, would not hesitate to apply his conclusions on Mars to the other planets. The *Astronomia Nova,* published in 1609, embodied the conclusions. But it contained much more as well. An intellectual autobiography, it described in detail every step of the investigation, so that we can follow the progress of Kepler's thought in a way that is possible with few other scientists. The progression of thought revealed was twofold—on the one hand, there was a movement away from the age-old obsession with circularity and toward the acceptance of noncircular orbits; on the other hand, there was a movement away from animistic modes of thought and toward a frankly mechanistic conception of the universe.

Ever since the flowering of Greek science, astronomy had attempted to account for celestial phenomena by combinations of uniform circular motions. The circle being the perfect figure, it alone was suitable to describe the heavens. Kepler too began his consideration of Mars with a circle, but from the beginning his treatment differed from earlier ones. Astronomers before him had combined circles—using a basic deferent, as it was called, with whatever combination of eccentrics and epicycles an individual might choose—to account for observed positions of the planets. (See Fig. 1.1.) The vectorial addition of the radii, laying them end to end, must place the planet where observations found it to be. In contrast, Kepler, who was convinced that new physical considerations must prevail, that crystalline spheres do not exist, but that planets nevertheless follow definite orbits through the immensity of space, was concerned from the beginning with the orbit itself. No previous theory had proposed that the path of a planet is a circle. Kepler first attempted to fit Mars to just such a circular orbit. Even in utilizing the circle, however, Kepler began to reject it, by denying uniform circular motion and accepting, as the evidence demanded, the proposition that Mars moves in its orbit with a varying velocity.

After Kepler had invested two years of effort in the theory, it finally failed. It contained an inaccuracy of 8′. Copernicus before him had been satisfied with an accuracy of 10′; Kepler could not forget, however, that Tycho's observations imposed a higher standard. "Since divine goodness has granted us a most diligent observer, Tycho Brahe, from whose ob-

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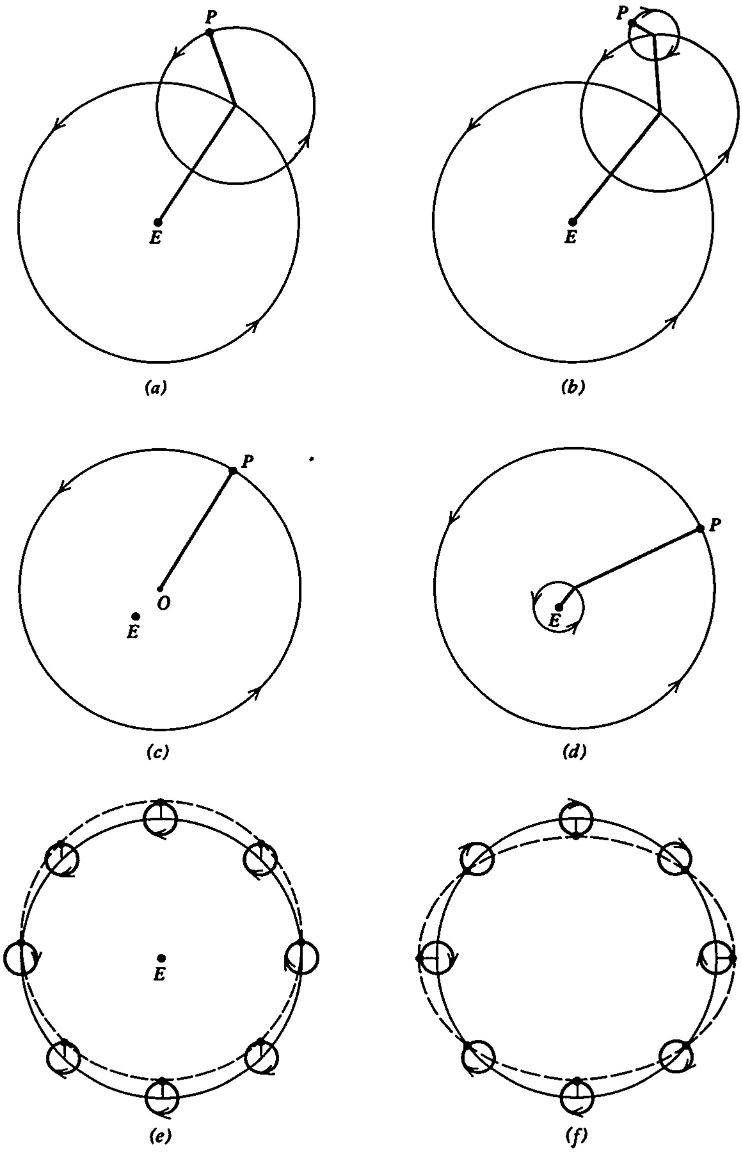

Figure 1.1. The geometrical devices of Ptolemaic astronomy. (a) *A major epicycle on a deferent.* (b) *An epicycle on a major epicycle.* (c) *An eccentric.* (d) *An eccentric on a deferent.* (e) *The effect of a minor epicycle with the same period as the deferent.* (f) *The effect of a minor epicycle with a period twice that of the deferent.*

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servations the error in this calculation of eight minutes in Mars is revealed, it is fitting that we recognize and make use of this good gift of God with a grateful mind." The first use of it he made was to reject the labor of two years.

Temporarily discouraged, Kepler turned from the orbit of Mars to the orbit of the earth. Extending the principles employed in his treatment of Mars, he concluded that the earth's velocity is inversely proportional to its distance from the sun. Kepler's "law of velocities," which Newton proved to be incorrect, served as a guiding beacon to his investigation. From it, he deduced the law of areas, which today we hold to be correct and call his second law of planetary motion. If the velocity varies inversely as the distance from the sun, the distance (or radius vector) from the sun of every small segment of the orbit must be proportional to the time the planet spends in traversing the segment. But the sum of radii vectors to the small segments of the orbit may be regarded as equal to the area that the radius sweeps out as the planet moves along. (See Fig. 1.2.) That is to say, the elapsed time is proportional to the area swept out. The mathematical reasoning was fallacious; never mind, the law of velocities used as a premise was also fallacious,

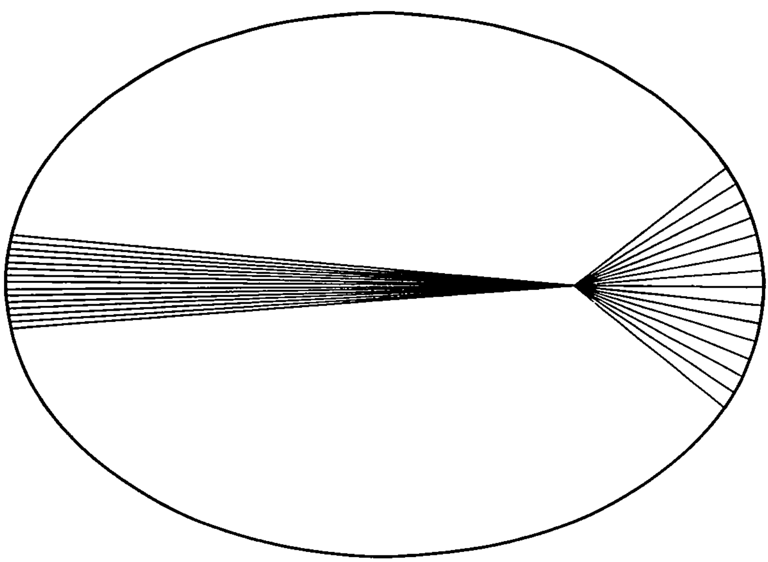

Figure 1.2. Kepler's law of areas. The eccentricity of the ellipse has been greatly exaggerated. The space between each pair of lines represents a single unit of time.

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but the conclusion has proved to be correct. The law of areas served a specific technical need. In the old astronomy of deferents and epicycles, the position of a planet could be calculated by the vectorial addition of radii, each of which turned at a uniform rate. Much of the power of the circle in astronomy consisted in its technical utility. Having abolished the machinery of multiple circles in favor of a single circle on which a planet moves with a nonuniform velocity, Kepler needed a formula by which to calculate the planet's position. This the law of areas supplied. And in supplying it, the law of areas made the circle dispensable in astronomy as it had never been before.

Kepler had derived the law of areas from the (erroneous) law of velocities. The law of velocities also suggested the basic elements of his celestial mechanics, which depended on the central dynamic function assigned to the sun. Kepler was convinced of the primary role of the sun in the universe. The source of all light and all heat, the sun must also be the source of all movement, the dynamic center of the solar system. Kepler imagined some power to radiate out from the sun, like the spokes of a wheel. As the sun turned on its axis the spokes would push the planets along. (See Fig. 1.3.) Nothing in Kepler's celestial mechanics operated to pull a planet aside from a tangential path and retain it in an orbit around the sun. The continuing hold of the circle over the thought even of the man who broke its grip on astronomy is attested by the fact that Kepler never doubted that planets would move round the sun in closed orbits if they moved at all. Obviously Kepler was employing the basic propositions of Aristotelian mechanics, according to which a body remains in motion only as long as something continues to move it, its velocity being proportional to the moving force. Thus the law of velocities appeared as an obvious consequence of the basic dynamics of the solar system. The effectiveness of the power radiating from the sun should decrease in proportion to the distance, and the velocity of each planet should vary inversely as its distance from the sun.

The more Kepler contemplated the dynamics of planetary motion, the more it recalled the basic relations of the lever. The farther a planet was removed from the sun, the less the power of the sun was able to move it. When the concept of a power radiating out from the sun first appeared in the *Mysterium Cosmographicum*, Kepler called it an *"anima motrix,"* a "motive soul," a phrase redolent of animistic connotations. In 1621, as he prepared a second edition of the *Mysterium*, he added a footnote: "If you substitute the word 'force' [*vis*] for the

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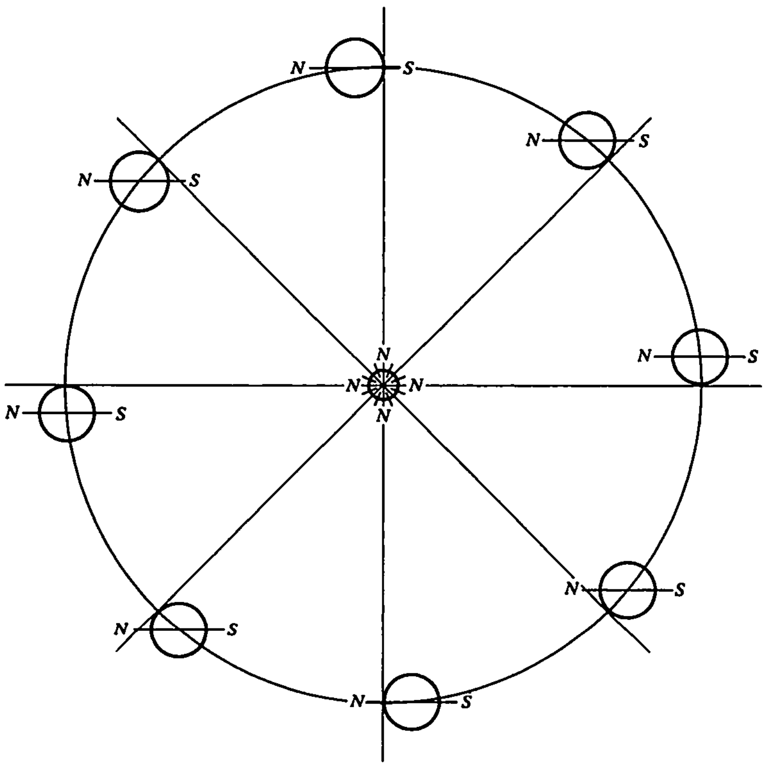

Figure 1.3. Kepler's celestial mechanics. As the planet circles the sun, the position of its axis maintains a constant alignment. The sun is a peculiar magnet, its surface constituting one pole and its center the other. Through half its orbit the planet is attracted toward the sun; through the other half it is repelled.

word 'soul' [*anima*], you have the very principle on which the celestial physics in the *Commentary on Mars* [*Astronomia Nova*] is based. For I formerly believed completely that the cause moving the planets is a soul, having indeed been imbued with the teaching of J. C. Scaliger on motive intelligences. But when I recognized that this motive cause grows weaker as the distance from the sun increases, just as the light of the sun is attenuated, I concluded that this force must be as it were corporeal." From *anima motrix* to *vis,* from the animistic to the mechanistic —the development in Kepler's thought foreshadowed the course of 17th century science.

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