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ASTRONOMY

William Donahue

In the late Middle Ages, astronomy, unlike most other natural sciences now recognized, had been studied and practiced for over two millennia. Together with the other ancient sciences of harmonics, optics, and mechanics, it was considered to be a mixed mathematical science, differing from the pure mathematical sciences – arithmetic and geometry – in that astronomy considered number and magnitude in bodies and not in themselves. In the application of this division (which was not always strictly followed), astronomy could only develop and apply mathematical hypotheses: Pronouncements about the true nature of the heavens lay within the province of natural philosophy.[1] Thus astronomers were not recognized as having the authority to decide whether the earth is moving or at rest, or whether comets are celestial or atmospheric. Astronomy's function was only to describe the apparent positions of the heavenly bodies for the purposes of timekeeping, calendar making, and prediction of celestial influences. (This last task was the function of astrology, which was a respected science in the late Middle Ages, dealing with the effects of the celestial motions, just as natural philosophy treated its causes.)

This division of the science was established on philosophical grounds, and was used by philosophers and physical theorists to keep astronomy and the other mathematical sciences in their place. Astronomers, on the other hand, were never entirely content with their marginalization, and, while they improved the predictive power of their science, they strove to show the natural philosophers that the claims of astronomy could not be ignored. In this the astronomers achieved remarkable success, and by the end of the seventeenth century, astronomy had become a near neighbor, or even a branch, of natural philosophy, even as natural philosophy itself came to be mathematized (see Blair, Chapter 17, this volume). At the same time, astrology gradually lost its academic respectability, largely because of its inability to adapt to the new astronomy and its adherence to an increasingly antiquated cosmology (see Rutkin, Chapter 23, this volume).

Both astronomy and astrology were academic subjects, taught and studied in the universities (though often outside of the regular curriculum). Although the astronomical tradition at the University of Paris, which had flourished in the thirteenth and early fourteenth centuries, had languished by 1500, the teaching of astronomy thrived at Oxford, Cracow, Prague, Vienna, and Bologna. Vienna in particular developed a strong astronomical tradition, beginning in the fourteenth century with Henry of Langenstein (ca. 1325–1397) and continuing with John of Gmunden (ca. 1380–1442), Georg Peurbach (1423–1469), and Johannes Regiomontanus (1436–1476). The latter two figure prominently in this chapter.[2]

The practice of astronomy, which was as a rule ancillary to the practice of astrology, was in contrast often carried on outside the universities. Rulers needed astrological predictions, which required knowledge of planetary positions, and physicians used the stars to plot the likely course of a disease. There was thus employment for astronomers at court, and the medical use of astrology greatly promoted the study and teaching of astronomy. Indeed, many of the most prominent astronomers of the period – one need mention only Nicholas Copernicus (1473–1543), Tycho Brahe (1546–1601), Johannes Kepler (1571–1630), and Galileo Galilei (1564–1642) – worked primarily or entirely outside the universities although all were university-educated (see Moran, Chapter 11, this volume).

Although there were numerous remarkable developments in astronomy in the sixteenth and seventeenth centuries, a broad theme that was common to many of them was the trend toward treating things in the sky as physical objects no different in principle from terrestrial objects. In this trend, there were two central figures: Galileo and Kepler. Galileo's first telescopic observations, published in *Sidereus nuncius* (Sidereal Messenger, 1610), gave a view of the heavens that was never before possible, affording close-up scrutiny of stars and planets. Kepler's theory of Mars's motion, *Astronomia nova* (New Astronomy, 1609), first introduced physical forces into a mathematically precise predictive apparatus. Each of these publications had a profound effect on the development of astronomy in the seventeenth century, but both in turn occurred in the context of well-developed astronomical and physical traditions.

Accordingly, this chapter begins by describing the sixteenth-century context in which questions about the heavens were formulated in the crucial period around 1610. Especially important was the significant role played by humanism in the works of Copernicus and other astronomical reformers, which recovered alternative ancient philosophical traditions that rivaled

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[1] See, for example, Aristotle, *Physics*, 2.2 (194a7); and James A. Weisheipl, "The Nature, Scope, and Classification of the Sciences," in *Science in the Middle Ages*, ed. David C. Lindberg (Chicago: University of Chicago Press, 1978), esp. pp. 474–80.

[2] Olaf Pedersen, "Astronomy," in Lindberg, ed., *Science in the Middle Ages*, pp. 329–30.

those of the Aristotelian schools and gave the mathematical sciences a more decisive role.

The themes that developed in the sixteenth century played out in different ways. Galileo's observations created an immediate sensation and were soon repeated and elaborated by other observers. Kepler's difficult theories, in contrast, were only gradually and partially accepted as their accuracy became recognized. The cosmological ideas of René Descartes (1596–1650) also did much to further the acceptance of physical arguments in astronomy. At the same time, the discovery of several evidently "new" stars (*novae*) prompted a search for more, which led to the discovery of variable stars and to the development of stellar astronomy as a distinct field of study. This chapter concludes with the publication of Isaac Newton's (1642–1727) *Principia mathematica philosophiae naturalis* (Mathematical Principles of Natural Philosophy, 1687 and 1713), which completely changed the way planetary theory was to develop.

ASTRONOMICAL EDUCATION IN THE EARLY SIXTEENTH CENTURY

In the early sixteenth-century university, astronomy was usually taught in two courses. The introductory course was based on the thirteenth-century *Sphere* of Johannes de Sacrobosco (d. 1244 or 1256), which described the parts of the celestial and terrestrial globes. More advanced instruction usually began with a study of a work called *Theorica planetarum* (Theories of the Planets), often attributed to Gerard of Cremona (1114–1187).[3] The *Theorica* and the tables derived from them were based on planetary models developed by the second-century Alexandrian astronomer Claudius Ptolemaeus (Ptolemy), sometimes with additions or modifications by later astronomers. In Ptolemy's models, a planet (P in Figure 24.1) moves on a circle (the epicycle, PQ in Figure 24.1) whose center, F is carried around a larger circle (the deferent, ABF), whose center, C, is fixed at a point near the earth (located at D). The center of the epicycle's motion on the deferent is not uniform about the deferent's center but moves with uniform angular motion about another point (the equant, E in Figure 24.1), which is twice as far from the earth, D, as the deferent's center, C (that is, $ED = 2CD$), and in the same line (the apse line, AB). Despite the availability of Ptolemy's major work, the *Almagest*, in Latin translations from both Arabic and the original Greek versions, it was seldom studied in university courses because of its difficulty.

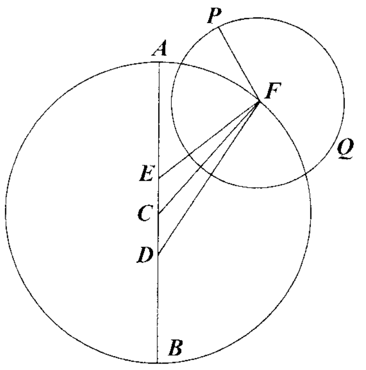

Figure 24.1. Ptolemaic planetary model.

The *Theorica* presented models of planetary motions in magisterial style, without explaining how they were arrived at or even whether they should be considered to represent anything real. An important advantage of this text was that it allowed the student to begin using astronomical tables, usually for astrological purposes, almost immediately. Such tables, in their simplest form, would give mean motions, positions of nodes and apses, and other parameters as a function of time, presented at convenient intervals. The practitioner would have to use one set of tables to find the position of the center of the epicycle on the deferent, then another to find the planet's place on the epicycle, and would then find the apparent position from these two by trigonometry. More advanced tables, such as the early fourteenth-century revision of the thirteenth-century Alfonsine Tables by John of Lignières, combined the two operations into a single large table, a great convenience. Early introduction to the use of tables was especially useful for medical students, who would need astrology for diagnostic and prognostic purposes.[4]

RENAISSANCE HUMANISM AND *RENOVATIO*

Peurbach, though often regarded as the first Renaissance astronomer, continued to develop the traditions of medieval astronomy. Nevertheless, in one respect at least, his work represented a departure from that of his predecessors. He was as much a humanist classicist as a mathematician, and endeavored to restore ancient learning from the ravages of scholastic mishandling. His

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[3] The *Sphere* is translated in Lynn Thorndike, *The Sphere of Sacrobosco and Its Commentators* (Chicago: University of Chicago Press, 1949). Selections are included in Edward Grant, ed., *A Source Book in Medieval Science* (Cambridge, Mass.: Harvard University Press, 1974), pp. 442–51. A complete translation (by Olaf Pedersen) of *Theoricae planetarum* is included in Grant, ed., *Source Book*, pp. 451–65. For more on the *Sphere*, the *Theoricae*, and astronomy in general, see the chapter on "Mediaeval Astronomy" in Olaf Pedersen and Mogens Pihl, *Early Physics and Astronomy: A Historical Introduction* (History of Science Library) (London: MacDonald, 1974), pp. 243–77.

[4] Nancy G. Siraisi, *Medieval and Early Renaissance Medicine: An Introduction to Knowledge and Practice* (Chicago: University of Chicago Press, 1990), pp. 67–8. For the Alfonsine Tables, see John North, *The Norton History of Astronomy and Cosmology* (New York: W. W. Norton, 1994), pp. 217–22.

most widely read work, *Theoricae novae planetarum* (New Theories of the Planets, 1472), aimed at replacing the medieval *Theorica planetarum*. In this, Peurbach was spectacularly successful: The *Theoricae novae* was in use well into the seventeenth century, with over fifty editions, translations, and commentaries published between 1472 and 1653.[5]

Peurbach had hoped to do more than just replace the standard textbook. Encouraged by his friend Cardinal Basilius Bessarion (ca. 1395–1472), he began work on a summary of Ptolemy's *Almagest* that was designed to introduce students to the study of the *Almagest* itself (although Peurbach was still relying on Gerard of Cremona's Latin retranslation from an Arabic version). Bessarion, Greek by birth, was papal legate to the imperial court in Vienna, where, in addition to his diplomatic duties, he worked to encourage the study of Greek classics. Peurbach died leaving this work unfinished, but it was taken up by his student Johannes Müller (1436–1476) of Königsberg (in what is now northern Bavaria), better known by his adopted surname Regiomontanus (Latinized from his birthplace). The *Epitome in Almagestum Ptolemaei* (Epitome on Ptolemy's Almagest), as the work was called, finally appeared in 1496. It was not just a summary of Ptolemy's masterpiece but included later observations, new computations, and some critical comments.[6] The classical tradition was thus being revived as a living body of theory, to be built upon or altered as circumstances required.

The importance of relating astronomy to the *Almagest* rather than to the tradition of the *Theorica* lay chiefly in the different ways of approaching the subject. Whereas the *Theorica* presented completed models without describing how they were constructed, Ptolemy showed how the orbital parameters could be derived from observations. This gave students of astronomy the ability to criticize existing models and revise or replace them.

A further instance of the humanist attempt not just to emulate classical models but to enter into their spirit and to improve them was the revival of the use of homocentric spheres in astronomy. Since the time of Ptolemy, an inconsistency had existed between Aristotle's physical account – homocentric because it restricted heavenly bodies to motion around the center of the universe (with which the center of the earth coincides) – and Ptolemy's use of eccentric circles and epicycles, which implied a very considerable variation in earth–planet distances. Aristotle had mentioned the efforts of Eudoxus to construct a viable homocentric theory, and Calippus's improvements of Eudoxus's models, without providing any details.[7] Some Islamic astronomers and philosophers, most notably al-Bitrūjī (ca. 1100–1185), known to the West by his Latinized name, Alpetragius, attempted a revival of the homocentrics.

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[5] E. J. Aiton, "Peurbach's *Theoricae novae planetarum*: A Translation with Commentary," *Osiris*, ser. 2, vol. 3 (1987), pp. 5–9.

[6] Joannes Regiomontanus, *Epitome in Almagestum* (Venice: Johannes Hamman, 1496); Aiton, "Peurbach's *Theoricae*," pp. 5–6; North, *The Norton History of Astronomy and Cosmology*, pp. 254–5.

[7] Aristotle, *Metaphysics*, 12.8 (1073b1–1074a18).

The work of al-Bitrūjī was translated into Latin in 1217 and spawned a number of other homocentric theories, among them one by Regiomontanus.[8]

In the early sixteenth century, there were two published attempts at homocentric theories: *De motibus corporum caelestium* (On the Motions of the Heavenly Bodies, 1536), by Giovanni Battista Amico (1512–1538), and *Homocentrica* (1538), by Girolamo Fracastoro (1478–1553). Although entirely inadequate for predicting planetary positions, these theories are notable in that they deliberately attempted to reconstruct the lost theories of Eudoxus. Fracastoro, whose work attained some degree of recognition, added the requirement that adjacent spheres have their axes at right angles – a fine example of the Renaissance tendency to want to go the ancients one better, particularly in adherence to principle – in this case, the Aristotelian principle that planetary motions must be simple and uniform.[9]

A similar motivation is evident in the work of Copernicus, who was a contemporary of Amico and Fracastoro and had received a thorough humanist education at Cracow and Bologna. In his *De Revolutionibus orbium coelestium* (On the Revolutions of the Heavenly Spheres, 1543), Copernicus objected in particular to two things in the *Almagest*: the introduction of nonuniform motions, and Ptolemy's failure to put the separate planetary models together into a systematic whole. On the former, he wrote: "Those who had devised eccentrics . . . had nonetheless admitted many things which appeared to go against the first principles concerning uniformity of motion."[10] That the heavens move with uniform circular motions was the most widely accepted axiom of the astronomers and was derived from the natural philosophical principle of celestial incorruptibility. Yet Ptolemy had supposed centers of uniform motion that were different from the centers of the circles on which the motions took place. Such motions, Copernicus complained, are really nonuniform in that they are in fact faster at one part of the circle and slower at another.

Copernicus's alternative model involved adding another small circle that adjusted the planetary motion enough to obviate the need for nonuniform motions. Similar models had in fact been proposed by Arabic astronomers, and Copernicus hints that he had used the Arabic models,

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[8] Pedersen and Pihl, *Early Physics and Astronomy*, pp. 266–7, 351, reissued as Olaf Pedersen, *Early Physics and Astronomy: A Historical Introduction*, rev. ed. (Cambridge: Cambridge University Press, 1993), pp. 235–6, 318; and N. M. Swerdlow, "Regiomontanus's Concentric-sphere Models for the Sun and Moon," *Journal for the History of Astronomy*, 30 (1999), 1–23.

[9] J. L. E. Dreyer, *A History of Astronomy from Thales to Kepler* (New York: Dover, 1953), pp. 296–304.

[10] Nicholas Copernicus, *De Revolutionibus* (Nuremberg, 1543), "Preface and Dedication to Pope Paul III," fol. iiiv; 4.2, fol. 99r-v, and 5.2, fol. 140v; Copernicus, *On the Revolutions*, translation and commentary by Edward Rosen (Baltimore: Johns Hopkins University Press, 1992) pp. 4, 176, 240. For a thorough discussion of the issues of uniformity and regularity, see Edward Grant, *Planets, Stars, and Orbs: The Medieval Cosmos, 1200–1687* (Cambridge: Cambridge University Press, 1994), pp. 488–94.

without mentioning specific names.[11] Evidently, like Fracastoro, Copernicus saw himself as not just reviving the ancient tradition but building upon it, not in a spirit of iconoclasm but of *renovatio*, of making it new once more.

Concerning the lack of a system in Ptolemy's universe, Copernicus used a simile drawn from Horace's *Ars Poetica*. "What happened to [the mathematicians]," he wrote, "is exactly as if one were to take from various places hands, feet, head, and other members, depicted indeed very well, but not for the composition of a single body, corresponding to each other not at all, so that a monster rather than a human being would be composed from them."[12] An explicitly humanist search through classical sources showed that some of the ancients had explained the heavenly phenomena by ascribing motion to the earth, so he thought that he, too, might be allowed that liberty. What Copernicus found was that "the order and sizes of the heavenly bodies and of all the orbs, as well as the heaven itself, are so connected that in no part of it can anything be displaced without disordering the remaining parts and the whole universe."[13] Here was an astronomical system that not only accounted for the phenomena of planetary motion but could lay claim to representing the physical truth.

To Copernicus's contemporaries, his achievement was not the theory of the earth's motion, but rather the composition of a modern rival to Ptolemy's *Almagest*, which in some respects surpassed its prototype. In its completeness and (not particularly successful) attempts at using recent observations to improve the accuracy of the theories, *De Revolutionibus* had no rival. It was used by Erasmus Reinhold (1511–1553), professor of mathematics at the University of Wittenberg, to construct a new set of planetary tables, the *Prutenic Tables* (1551), which were widely used and were reprinted in 1585. However, during the entire sixteenth century, hardly any readers of *De Revolutionibus* had anything good to say about its assertion of earth's triple motion (rotation on its axis, revolution about a point near the sun, and directional rotation of its axis).[14] This was partly because of the preface "To the Reader, on the Hypotheses of this Work," which claimed that astronomy "does not think up [hypotheses] in order to persuade anyone of their truth, but only

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[11] Copernicus, *De Revolutionibus*, 34. The manuscript version of this chapter has a passage, later deleted, that ascribes one of these models to "certain people" (*aliqui*). See *Nicolaus Kopernikus Gesamtausgabe, Band I: Opus De Revolutionibus Caelestibus Manu Propria Faksimile-Wiedergabe* (Munich: Oldenbourg, 1944), fol. 75v; Rosen translation, p. 126.

[12] Copernicus, *De Revolutionibus*, fol. iiiv; Horace, *Ars Poetica*, lines 1–13; cf. Robert S. Westman, "Proof, Poetics, and Patronage: Copernicus's Preface to *De revolutionibus*," in *Reappraisals of the Scientific Revolution*, ed. David C. Lindberg and Robert S. Westman (Cambridge: Cambridge University Press, 1990), pp. 179–84.

[13] Copernicus, *De Revolutionibus*, fol. ivr.

[14] This last motion was an artifact of astronomers' use of an early version of polar coordinates, that required the axis to be cranked around in order to make the north pole face toward the sun at one side of its orbit and away from it at the opposite side. Kepler was the first to point out that this was not a real motion. See Kepler, *Epitomes astronomiae Copernicanae*, I (Linz, 1618), para. 5 sect. 5, pp. 113–4, in *Johannes Kepler Gesammelte Werke* (Munich: C. H. Beck, 1937–), vol. 7 (1953), pp. 85–6.

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But even without Osiander's preface, the idea of a moving earth was unlikely to convince many readers. It too blatantly contradicted current theories of motion and left too many questions unanswered. How could the sluggish earth carry out the complicated triple motions assigned to it? Why would God create so much empty space between Saturn and the fixed stars?[16] Drastic changes in cosmological ideas, and in the way natural philosophy was done, would have to occur first in order to provide a context in which a moving earth made sense.

CRACKS IN THE STRUCTURE OF LEARNING

One important source of change was the assortment of alternatives to scholastic natural philosophy, and, indeed, the more subtle changes that were taking place in scholastic natural philosophy itself. Of particular interest are authors of philosophical works who believed it to be within the competence of mathematics to make valid judgments about physical reality. Nicholas of Cusa (1401–1464), a Catholic cardinal, was especially remarkable for his view that the mind and the truth it grasps are, at the deepest level, based on magnitude (either numerical or geometrical). Interestingly, he argued, a century before Copernicus, that the earth moves, though the basis for his claim had little to do with astronomy and much to do with theology. Evidently, at least

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[11] Copernicus, *De Revolutionibus*, 34. The manuscript version of this chapter has a passage, later deleted, that ascribes one of these models to "certain people" (*aliqui*). See *Nicolaus Kopernikus Gesamtausgabe, Band I: Opus De Revolutionibus Caelestibus Manu Propria Faksimile-Wiedergabe* (Munich: Oldenbourg, 1944), fol. 75v; Rosen translation, p. 126.

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[15] For Reinhold, see C. C. Gillispie, ed., *Dictionary of Scientific Biography* (New York: Scribners, 1970–90), 11: 365–7; and Owen Gingerich, "The Role of Erasmus Reinhold and the Prutenic Tables in the Dissemination of Copernican Theory," in *Colloquia Copernicana*, II, ed. Jerzy. Dobrzycki (Wrocslashelaw;Ossolineum 1973), pp. 43–62, 123–5. For Osiander, see Edward Rosen's notes to Copernicus, *On the Revolutions*, pp. 333–5; Bruce Wrightsman, "Andreas Osiander's Contribution to the Copernican Achievement," in *The Copernican Achievement*, ed. Robert S. Westman (Berkeley: University of California Press, 1975), pp. 213–43; and Nicholas Jardine, *The Birth of History and Philosophy of Science: Kepler's "A Defence of Tycho against Ursus," with Essays on Its Provenance and Significance* (Cambridge: Cambridge University Press, 1984), pp. 150–4. Kepler's publication of the evidence of Osiander's authorship is on the verso of the title page of *Astronomia nova* (Heidelberg: Vögelin, 1609); see Johannes Kepler, *New Astronomy*, trans. William H. Donahue (Cambridge: Cambridge University Press, 1992), pp. 28–9.

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the upper echelons of the Church in the fifteenth century could prove more congenial to bold speculation than did the universities.[17]

But despite the freedom afforded by his secure position, Nicholas of Cusa enjoyed only moderate success in finding an audience for his ideas. One influential follower was the Carthusian prior Gregor Reisch (ca. 1467–1525), whose philosophical textbook, *Margarita philosophica* (The Philosophical Pearl, 1503), was widely used and often reprinted throughout the sixteenth century. In most respects, the *Margarita* was anything but revolutionary. But Reisch cited Nicholas of Cusa in support of the inclusion of astronomy and the other mathematical arts under philosophy, classifying them as "speculative philosophy of [material] things."[18] A similar, and perhaps related, tendency may be seen in the teaching of Reinhold at Wittenberg in 1536. Introducing Euclid and Peurbach to his students, he said that "that part of Philosophy that is called 'Physica' takes its origin from Geometry." This thoroughly un-Aristotelian opinion, adumbrating a new, mathematically based view of the entire physical cosmos, could have come directly from Nicholas of Cusa's *Idiota de mente* (The Layman: About Mind), published in 1450.[19]

In the decades following the publication of *De Revolutionibus*, a lively variety of publications appeared that challenged conventional physical theory, including the physics of the heavens. Authors who challenged Aristotle's radical distinction between the pure eternal celestial aether and the four "sublunar" elements of air, earth, fire, and water include the Milanese physician, astrologer, and mathematician Girolamo Cardano (1501–1576), the iconoclastic German physician Theophrastus Bombastus von Hohenheim, known as Paracelsus (1493–1541); Francesco Patrizi (1529–1597), professor of Platonic philosophy at La Sapienza (the University of Rome); Bernardino Telesio (1509–1588), lecturer at the University of Naples; and the Dominicans Tommaso Campanella (1568–1639) and Giordano Bruno (1548–1600) (see Garber, Chapter 2, this volume). Perhaps following Stoic authors, Cardano denied that fire is an elementary substance, thus reducing the number of elements to three. The heavens, in his view, were the source of warmth. By thus removing the sphere of fire that Aristotle had located beneath the lunar spheres, Cardano created a continuity that brought heaven and earth closer together. Accordingly, he believed that comets, which were traditionally

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[17] A useful biographical sketch and introduction to Nicholas of Cusa's work, with many references, is included in Nicholas de Cusa, *Unity and Reform: Selected Writings*, ed. John Patrick Dolan (Notre Dame, Ind.: University of Notre Dame Press, 1962), pp. 3–53. A succinct statement of Nicholas's view on the mind's operation is presented in Nicholas de Cusa, *Idiota de mente (The Layman: About Mind)*, trans. and intro. Clyde Lee Miller (New York: Abaris Books, 1979), chap. 10, p. 75.

[18] Gregor Reisch, *Margarita philosophica* (Freiburg im Breisgau: J. Schott, 1503), fol. [ ] 4r; cf. bk. 4, pt. 1, chap. 1 for the importance of mathematics and a citation of Nicholas of Cusa.

[19] *Scriptorum publice propositorum a professoribus in Academia Witebergensi ab anno 1540 usque ad 1553, tomus primus* (Wittenberg: G. Rhaw, 1560), quoted in Sachiko Kusukawa, *The Transformation of Natural Philosophy: The Case of Philip Melanchthon* (Cambridge: Cambridge University Press, 1995), p. 180; cf. Nicholas de Cusa, *Idiota de mente*, chap. 10, p. 75.

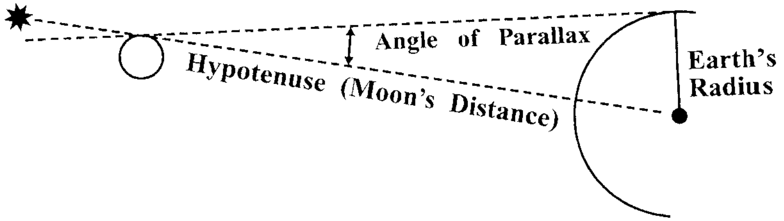

Figure 24.2. Diurnal parallax of the moon.

supposed to be atmospheric, could enter the celestial regions and might even originate there. Cardano proposed measuring their distance by means of parallax observations, which were well known to astronomers because the lunar parallax had to be considered in predicting eclipses. (Parallax is the measure of how much a relatively nearby object appears to move against a distant background because of a displacement of the observer; Figure 24.2 illustrates how diurnal parallax affects the observed position of the moon.) Cardano does not appear to have made any such observations himself, however.[20]

Paracelsus, though an eclectic, drew his worldview primarily from the tradition of alchemy (see Newman, Chapter 21, this volume). Although he had little directly to say about the heavens, his magico-chemical worldview, with three principles (identified with sulfur, salt, and mercury), attracted many followers, including the influential Danish astronomer Tycho Brahe, who was also interested in alchemy. Paracelsus held that the heavens are not radically different from the terrestrial and atmospheric regions and believed the stars to be fiery in nature.[21]

Patrizi, Campanella, and Bruno were all strongly influenced by the supposedly ancient philosophical and mystical tradition stemming from the legendary Hermes Trismegistus, the central characteristic of which was a belief that nature, both as a whole and in each part, is alive and possessed of a soul that governs all of its operations[22] (see Copenhaver, Chapter 22,

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[20] William H. Donahue, *The Dissolution of the Celestial Spheres, 1595–1650* (New York: Arno Press, 1981), pp. 51–2; and C. Doris Hellman, *The Comet of 1577: Its Place in the History of Astronomy* (Columbia University Studies in the Social Sciences, 510) (New York: Columbia University Press, 1944; New York: AMS Press, 1971), pp. 90–6.

[21] For Paracelsus, see Walter Pagel, "Paracelsus," in Gillispie, ed., *Dictionary of Scientific Biography*, 10: 304–13. On the celestial generation of comets, see Paracelsus, *Opera* (Geneva: J. Anton & S. De Tournes, 1658), 2: 318, cited in *Tychonis Brahei Dani opera omnia*, ed. J. L. E. Dreyer, 15 vols. (Copenhagen: Libraria Gyldendaliana, 1913–29), vol. 4 (1922), pp. 511–12. For Brahe's Paracelsian education, see Victor Thoren, *The Lord of Uraniborg: A Biography of Tycho Brahe* (Cambridge: Cambridge University Press, 1990), pp. 24–5.

[22] Frances A. Yates, *Giordano Bruno and the Hermetic Tradition* (London: Routledge and Kegan Paul, 1964), is a thorough treatment of Renaissance Hermeticism and includes discussions of all of these authors. A briefer account, focused more closely on cosmology and astronomy, is in Donahue, *The Dissolution of the Celestial Spheres*, pp. 41–53. For Bruno, see Paul-Henri Michel, *The Cosmology of Giordano Bruno* (Ithaca, N.Y.: Cornell University Press, 1973); and Giordano Bruno, *The Ash Wednesday Supper*, ed. and trans. Edward A. Gosselin and Lawrence S. Lerner (Hamden, Conn.:

this volume). Despite considerable differences in their development of this philosophy, they were easily identifiable by their contemporaries as followers of Hermetic neo-Platonism, and this identification inevitably colored the way in which their works were read.[23] The idea of a world soul, in particular, was theologically suspect, and all of these authors were charged with various degrees of heresy during the last decade of the sixteenth century. So even though Campanella wrote a book in support of Galileo and Bruno argued for a heliocentric planetary system within an infinite universe, such heterodox writers were generally opposed by proponents of the new approach to nature, including Kepler, Galileo, and Descartes. Moreover, the difference here was not only a matter of political prudence (Bruno had been burned at the stake for heresy): The Hermetics tended to be more interested in numerology than mathematics and scorned the mixed mathematical sciences, astronomy in particular.[24]

The importance of all of these alternative theories was not their explanatory power, or their provision of a possible replacement for scholastic natural philosophy but simply their existence. They represented a sense of the richness of the various traditions that were being rediscovered and the comparative limitations of what was taught in the schools. And even academic accounts of the nature of the heavens were beginning to change, incorporating Stoic ideas and scripturally based alternatives to Aristotle (see Blair, Chapter 17, this volume).[25]

It is clear that whatever the causes, during the sixteenth century there was an increasing tendency on the part of natural philosophers as well as astronomers to consider the heavens as being made of stuff not radically different from earthly matter. At the beginning of the century, scholastic discussions of celestial matter centered around such questions as whether the heavens consist of form and matter or are mere forms (being immaterial). The question of whether the celestial orbs (if they are real) were solid (i.e., hard) or fluid was not even raised in natural philosophy courses before the 1580s. By the early seventeenth century, this question became quite common in school texts. Even for those who followed Aristotle, the heavens were by this time thought to be composed of something that is extended, noninterpenetrable, and (usually) hard and rigid.[26]

THE REFORMATION AND THE STATUS OF ASTRONOMY

Moreover, the schools themselves were undergoing change, especially as a result of the Reformation. Martin Luther (1483–1546) was no admirer of the scholastic philosophies that had served to buttress what he saw as corrupt Catholic doctrines, and the universities in Lutheran lands seemed for a time in danger of falling apart. Seeing the negative consequences that would result from such an event, Luther charged his friend and associate, the humanist scholar Philip Melanchthon (1497–1560), with the mission of developing a reformed system of higher education. Melanchthon's system emphasized ethics. It involved the elimination of much of philosophy and favored sciences that had practical value. Astronomy was retained largely because of its utility in supporting astrology, particularly medical astrology. Melanchthon himself wrote in praise of astronomy, and in his reorganization of the University of Wittenberg he founded a distinctly Lutheran tradition of astronomical instruction and theory.[27]

The Wittenberg school characteristically held Copernicus in high regard while, on the whole, rejecting his systematic claims and his moving earth. Copernicus was seen as having superseded Ptolemy in the consistency and accuracy of his planetary models and so was not to be ignored. This approach suggested that the individual planetary models be revised in accord with the supposition of a central and motionless earth. The *Prutenic Tables* of Wittenberg mathematics professor Reinhold were constructed in this way. Similar views were expressed by Reinhold's successor and Melanchthon's son-in-law Caspar Peucer (1525–1602), Peucer's student Michael Praetorius (1537–1616), and others.[28] This "Wittenberg interpretation" had the effect of encouraging the study of Copernicus's work (which had been reprinted in 1566), thus preparing the way for a serious consideration of the systematic advantages of heliocentrism.

Archon Books, 1977); the introduction to this work is a good brief account of Bruno and his thought. For Campanella, see Tommaso Campanella, *A Defense of Galileo, the Mathematician from Florence*, trans. Richard J. Blackwell (Notre Dame, Ind.: University of Notre Dame Press, 1994).

[23] Patrizi acknowledges his Hermeticism in his dedication to Pope Gregory XIV, *Nova de universis philosophia* (Venice: Robertus Meiettus, 1593). For Campanella's and Bruno's Hermetic ideas, see Yates, *Giordano Bruno and the Hermetic Tradition*, esp. chap. 20.

[24] For Patrizi's view of astronomy, see Patrizi, *Nova de universis philosophia* "Pancosmia," bk. 12, fol. 91, col. 2. For Bruno, see Michel, *The Cosmology of Giordano Bruno*, esp. pp. 190–8; and Yates, *Giordano Bruno and the Hermetic Tradition*, pp. 235–41. On Hermetic mathematics in general, see Johannes Kepler, *Pro suo opere Harmonices mundi apologia* (Frankfurt: G. Tampach, 1622), p. 34, in Kepler, *Gesammelte Werke*, vol. 6: *Harmonices mundi* (1940), p. 432; and W. Pauli, "The Influence of Archetypal Ideas on the Scientific Theories of Kepler," in C. G. Jung and W. Pauli, *The Interpretation of Nature and the Psyche* (London: Routledge and Kegan Paul, 1955), pp. 190–200.

[25] Peter Barker and Bernard R. Goldstein, "Is Seventeenth Century Physics Indebted to the Stoics?," *Centaurus*, 27 (1984), 152–4; Peter Barker, "Stoic Contributions to Early Modern Science," in *Atoms, Pneuma, and Tranquillity: Epicurean and Stoic Themes in European Thought*, ed. Margaret J. Osler (Cambridge: Cambridge University Press, 1991), pp. 135–54; Grant, *Planets, Stars, and Orbs*, p. 267; and Donahue, *The Dissolution of the Celestial Spheres*, pp. 53–9.

[26] Léon Blanchet, *Les antecédents historiques du je pense, donc je suis* (Paris, 1920), p. 69; and Sister Mary Richard Reif, "Natural Philosophy in Some Early Seventeenth Century Scholastic Textbooks," Ph.D. dissertation, St. Louis University, St. Louis, Mo., 1962, pp. 83–97.

[27] Kusukawa, *The Transformation of Natural Philosophy*, pp. 27–74, 171–200.

[28] Robert S. Westman, "The Wittenberg Interpretation of the Copernican Theory," in *The Nature of Scientific Discovery*, ed. Owen Gingerich (Washington, D.C.: Smithsonian, 1995), pp. 393–429; Robert S. Westman, "Three Responses to the Copernican Theory: Johannes Praetorius, Tycho Brahe, and Michael Maestlin," in Westman, ed., *The Copernican Achievement*, pp. 285–345; and Thoren, *The Lord of Uraniborg*, p. 86.

Although the Lutherans were by no means the only cultivators of astronomy, this tradition is worthy of special attention because the most significant astronomers of the late sixteenth and early seventeenth centuries, Brahe and Kepler, were grounded in this tradition. Brahe had begun his studies at the University of Copenhagen, where Melanchthon's influence was strong, and continued them at the University of Leipzig, studying astronomy under Bartholomaeus Scultetus (1540–1614), protegé and successor of Wittenberg alumnus Johannes Homelius (1518–1562). Kepler was a student of Michael Maestlin (1550–1631), and both had been educated at the Lutheran University of Tübingen.[29]

We do not have much evidence of Brahe's early opinions of the heliocentric system, though it is clear that, like the Wittenberg astronomers, he admired the specific Copernican arrangements of circles in the planetary models. However, later publications and letters show that he was troubled by the physical and scriptural obstacles to a moving earth, and by the enormous distances of the fixed stars that Copernicus's system implied. In response to these difficulties, Brahe proposed a compromise system, announced in a chapter added to a work on the comet of 1577 published in 1588 (Figure 24.3).[30] In the so-called Tychonic system, which was intended to satisfy both the astronomers and the philosophers, all planets circle the sun, which in turn orbits around a motionless earth. With this schema as a guide, Brahe hoped to construct better models of planetary motions. Using both his income as a Danish nobleman and supplementary royal grants, he established a major observatory and fitted it with instruments of unprecedented size and accuracy, complementing his superb skill as an observer. From Uraniborg, "The Castle of Urania" (muse of astronomy), as Brahe called his island observatory, he carried out an unprecedented series of observations involving multiple sequential sightings of planets at important points on their paths, as well as a completely new set of coordinates for more than a thousand fixed stars. The planetary theories that he hoped would be built on these observations would not only be far more accurate than their predecessors but could also plausibly lay claim to being true, or at least more nearly true than Ptolemy's or Copernicus's constructions.

Yet Brahe's work also contained within itself the means by which his system was to be undone. He was familiar with Cardano's views on comets, and, as mentioned previously, was partial to Paracelsian ideas.[31] Furthermore, his

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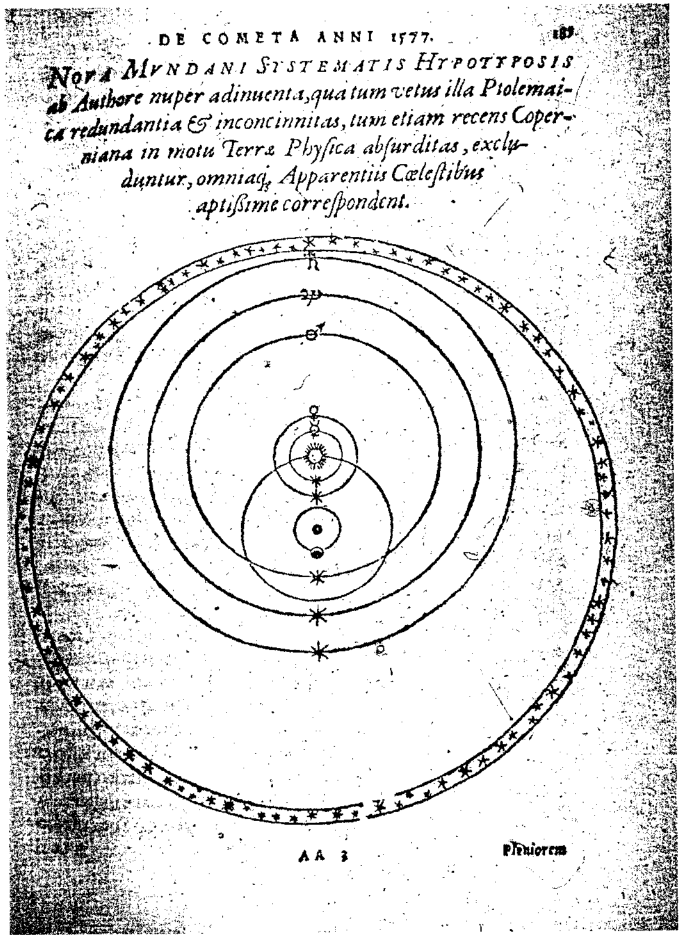
[29] Thoren, *The Lord of Uraniborg*, pp. 9–12, 42; Westman, "The Wittenberg Interpretation," pp. 393–429; and Westman, "Three Responses," pp. 329–30.

[30] Tycho Brahe, *De mundi aetherei recentioribus phaenomenis* (Hven: Christophorus Vveida, 1588), chap. 8, in *Opera omnia*, vol. 4 (1922), pp. 155–70. For Brahe's arguments against the heliocentric system, see J. L. E. Dreyer, *A History of Astronomy from Thales to Kepler* (New York: Dover, 1953), pp. 360–5, and the sources cited therein. Brahe's development of his system is described in Thoren, *The Lord of Uraniborg*, chap. 8, pp. 236–64.

[31] Hellman, *The Comet of 1577*, p. 92; Brahe, *De cometa anni 1577*, in *Opera omnia*, vol. 4 (1922), pp. 382–3.



DE COMETA ANNI 1577. 189

NOVA MVNDANI SYSTEMATIS HYPOTYPOSIS ab Authore nuper adinuenta, qua tum vetus illa Ptolemaica redundantia & inconcinnitas, tum etiam recens Copernicana in motu Terræ Phyſica abſurditas, excluduntur, omniaq; Apparentiis Cœleſtibus aptiſsime correſpondent.

AA 3 Pleniorem

Figure 24.3. Tychonic system. In Tycho Brahe, *De mundi aetherei recentioribus phaenomenis* (Uraniborg: [By the author, 1588]), p. 189. Photograph courtesy of Owen Gingerich.

planetary system required the circles of several planets, and of Mars in particular, to cross the orb of the sun. Brahe was therefore inclined to suspect that the spheres of the astronomers might not be physically real. Accordingly, some of his earliest and most important observations were careful measurements of the parallax of comets, with the aim of determining their altitude above earth. Suspecting that the standard Aristotelian view of comets as vaporous terrestrial exhalations might be wrong, and that they might in fact be celestial bodies, Brahe applied astronomical instruments and methods to them. Having found the parallax to be very small, he concluded that comets must be in the heavens and that the comet of 1577 passed through the region that, according to traditional astronomy, is occupied by the set of spheres carrying the planet Venus. Here was the proof Brahe sought that no such spheres exist: The planets were free to follow their appointed paths in an unobstructed space.[32]

Although this solved Brahe's immediate problem of the intersecting orbs, it raised a new one: How, in the absence of the orbs to carry them, could the planets be made to move in the complex paths required of them by this system? Brahe himself addressed this question only obscurely, combining Stoic and Paracelsian ideas in making the planets and stars self-moving fiery beings.[33] This did little to settle the matter, and the question of the causes of planetary motion became an important question, perhaps the most important question, for astronomers and natural philosophers of the seventeenth century. And, as it turned out, no one was able to give a satisfactory answer in the context of the Tychonic planetary arrangement.

But although his system was ultimately unsuccessful, Brahe's role in the development of astronomy can hardly be overstated. His skill as an observer and instrument designer was celebrated, and he was especially innovative in setting up his own workshop where observers and artisans could work together (see Cooper, Chapter 9, this volume). On the theoretical level, Brahe built upon the Wittenberg tradition of competence in mathematical astronomy while seeking to harmonize astronomy and natural philosophy.

This attempt to forge a synthesis was by no means unprecedented. Numerous astronomers proposed planetary theories that were intended to be physically sound. On a more empirical level, there was a long tradition of comet observations, going back at least to the fourteenth century, which led to the formulation of a non-Aristotelian theory that allowed comets to exist in the planetary regions.[34] Such theories had been ignored by earlier natural philosophers on the grounds that their discipline, being the superior one, was under no obligation to accommodate itself to astronomy.

Yet Brahe was remarkably successful in winning acceptance for his conclusions, even among academic natural philosophers. This was partly because, as already mentioned, the natural philosophers were ready to make the accommodation of co-opting non-Aristotelian ideas and making their heavens a little more earthlike. But Brahe's success also depended on his unusual status as a nobleman and an independent practitioner of his art. He, as well as his contemporary William IV (1532–1616), Landgrave of Hesse, reinvented the state-supported observatory as an institution, which had been invented by Islamic astronomers in the thirteenth century.[35] These two independent astronomers had the economic and social wherewithal to produce unimpeachable results and to promulgate them to a wide audience. Thus Brahe's careful collation of his own observations of the 1577 comet with those of many other observers came to be cited by later writers, both astronomers and philosophers, as establishing the celestial position of comets and the nonexistence of planetary spheres.[36] A profound change had occurred in astronomy's standing as a natural science: After the second decade of the seventeenth century, astronomy's authority in the realm of physics was never seriously questioned.

In bringing about this change, a crucial role was played by the educational system built by the Jesuits, and especially their leading institution, the Collegio Romano, and its mathematics professor, Christoph Clavius (1538–1612). Clavius had done much to advance the standing of mathematics, including astronomy, in the Jesuit curriculum, and wrote one of the most influential introductory astronomical textbooks of the late sixteenth century, a lengthy commentary on the *Sphere* of Sacrobosco.[37] While adhering to a traditional Aristotelian framework and style of reasoning, Clavius and his Jesuit colleagues and students kept up with new discoveries and theories, such as the relocation of comets to the heavens, the celestial position of new stars (*novae*), and the invention of the telescope. Their influence is indisputable: By 1600 there were over 250 Jesuit colleges in Europe, and Jesuit missionaries were traveling the world, spreading Brahe's, and later Newton's, astronomical theories, and Galileo's telescope, as far as Japan and China. Nor were the Jesuits the only proponents of this moderate reformist position: Several professors at Louvain, a small group in Copenhagen, and other individuals elsewhere were expressing similar views in the first two decades of the seventeenth century.[38]

ASTROLOGY

Astrological theory was quite distinct from astronomy, taking the planetary motions as given and considering their supposed effects (see Rutkin, Chapter 23, this volume). However, because some degree of technical competence was required to cast a horoscope, astrology was usually practiced by those with astronomical training. Kepler likened astrology to a foolish but

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[32] Brahe, *De mundi aetherei recentioribus phaenomenis*, chap. 6, pp. 89–158, in *Opera omnia*, 4: 82–134; cf. the diagram on p. 203 (chap. 7) showing the comet's position in relation to Venus's orb. See also Hellman, *The Comet of 1577*, pp. 121–37.

[33] Brahe, *Epistolae astronomicae liber primus* (Uraniburg, 1596), in *Opera omnia*, vol. 6 (1919), pp. 166–7; cf. Peter Barker, "Stoic Contributions," p. 146.

[34] Peter Barker and Bernard R. Goldstein, "The Role of Comets in the Copernican Revolution," *Studies in the History and Philosophy of Science*, 19 (1988), 299–319.

[35] North, *The Norton History of Astronomy and Cosmology*, pp. 192–202.

[36] Donahue, "The Solid Planetary Spheres," pp. 259–63; Grant, *Planets, Stars, and Orbs*, pp. 345–61.

[37] For Clavius and the Jesuits, see James M. Lattis, *Between Copernicus and Galileo: Christopher Clavius and the Collapse of Ptolemaic Cosmology* (Chicago: University of Chicago Press, 1994).

[38] Donahue, *The Dissolution of the Celestial Spheres*, pp. 53–9, 114–24; North, *The Norton History of Astronomy and Cosmology*, pp. 147–53.

well-off daughter, without whose help mother astronomy would starve. In astrology, as in astronomy, Ptolemy was the chief authority, although the ninth-century Persian astronomer Abū Maʿshar (Albumasar) made substantial contributions to astrological theory and practice. Its theoretical basis was in natural philosophy: In the Aristotelian cosmos, the function of the planetary motions was to stir up the terrestrial elements and make things happen on earth and in the air.[39] There was therefore general agreement, among proponents and opponents of astrology alike, that the stars influenced events on earth. Indeed, some of these influences are obvious, such as those of the sun and moon on days and nights, seasons, and tides. Criticism of astrology focused on whether astral influences could be known and whether astrology as then practiced represented the influences correctly. This was difficult to determine in any theoretical way because astrological principles (such as the properties of the zodiacal signs) were stated dogmatically rather than being deduced from natural causes. Astrology's putative veracity depended upon testimony of many authorities (Plato, Aristotle, Virgil, Ovid, Albumasar, Pliny, the legendary Hermes Trismegistus, Thomas Aquinas, and many others) and upon experience. Thus, oddly, it was one of the most nearly empirical of the sciences; then, as now, one would come to believe in it by practicing it.[40]

Astrology figured prominently in the reformed Lutheran curriculum at the University of Wittenberg that was developed by Melanchthon. In the early stages of this reform, astrology was included because of its practical value in medicine, and in turn it provided the justification for the teaching of astronomy and physics. Later, Melanchthon defended the study of astrology because of its demonstration of the workings of divine providence. His support of astrology thus helped establish a tradition of cultivating astronomy and astrology in Lutheran universities. Astrology was also often studied outside the universities through the reading of texts and the sharing and discussion of horoscopes of notable persons.[41]

Astrology had a number of different branches, some of which were more widely accepted than others. One of its most common uses was in weather prediction, an application very important to agriculture. The writing of calendars and almanacs containing astrological weather forecasts was one of the functions of mathematicians with official appointments. Kepler, who held a number of posts, including that of imperial mathematician, wrote many such calendars and was proud of the success of his predictions. Another common use was in medical diagnosis. Medical astrology had a long and distinguished history and appears to have motivated a number of early observers. For instance, some of the earliest comet observations were made by physicians (e.g., by Geoffrey of Meaux in 1315, Jacobus Angelus in 1402, Peter of Limoges in 1299, and Paolo Toscanelli from 1433 to 1472), who usually included astrological considerations in their accounts.[42]

The most frequently condemned branch of astrology was so-called judicial astrology, which involved drawing up "nativities," or horoscopes, for individuals. This was suspect not because it had a less solid theoretical foundation than the other branches but because it encroached on the delicate matter of free will and responsibility for sin. Accordingly, those who rejected it often did so for religious reasons: The Swiss religious reformer John Calvin (1509–1564), for example, accepted medical and natural uses of astrology but condemned judicial astrology. Those who defended judicial astrology stressed that the stars incline but do not compel.[43]

The most effective critique of astrology, however, came from the humanist philosopher Giovanni Pico della Mirandola (1463–1494). Pico's two main arguments were, that even among astrologers there was much disagreement about effects and that attempts to explain astrological influences were mostly based on fanciful analogies rather than sound physical reasoning. Although he believed that the motions of the heavens had effects on earth, he also believed that the human soul was free and not subject to astral influences.[44]

Pico's arguments attracted considerable attention throughout the sixteenth century and were carefully considered by Kepler in formulating his revision of astrology at the beginning of the seventeenth century. Defenders of astrology, interestingly, often adduced empirical criteria in their defense, giving examples of astrology's successful predictions and the overwhelming support of those who had studied the art. It was noted that Pico himself

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[39] Aristotle, *On the Heavens*, 2.3; *On Generation and Corruption*, 2.10. For Kepler's simile, see *De stella nova* (Prague, 1606), chap. 12, in *Gesammelte Werke*, vol. 1 (1937), p. 211. For a more complete account of the roots of European astrology, see J. D. North, "Medieval Concepts of Celestial Influence: A Survey," in *Astrology, Science, and Society*, ed. Patrick Curry (Woodbridge: Boydell Press, 1987), pp. 5–17.

[40] See, for example, Kepler's quotation of Brahe's remark (in Kepler's unpublished *De directionibus* of 1601) that "in astrology, as in theology, one must not seek for reasons, but only believe, insofar as the latter is from authority, and the former from experience." In *Ioannis Kepleri astronomi opera omnia*, ed. C. Frisch, 8 vols. (Frankfurt and Erlangen: Heyder and Zimmer, 1858–71), vol 8.1 (1870): 295. For authorities cited in support of astrology, see Wayne Shumaker, *The Occult Sciences in the Renaissance: A Study in Intellectual Patterns* (Berkeley: University of California Press, 1972), pp. 27–30, 35–6.

[41] Siraisi, *Medieval and Early Renaissance Medicine*, pp. 67–8; Kusukawa, *The Transformation of Natural Philosophy*, pp. 61, 129–59; and Anthony Grafton, *Cardano's Cosmos: The Worlds and Works of a Renaissance Astrologer* (Cambridge, Mass.: Harvard University Press, 1999), pp. 35–7, 42–3, 71–5.

[42] Max Caspar, *Kepler*, trans. C. Doris Hellman (New York: Dover, 1993), pp. 58–60, 154–6, 172; Siraisi, *Medieval and Early Renaissance Medicine*, pp. 68, 135; Barker and Goldstein, "The Role of Comets in the Copernican Revolution," pp. 308–10; and Lynn White, Jr., "Medical Astrologers and Medieval Technology," in White, *Medieval Religion and Technology* (Berkeley: University of California Press, 1978), pp. 297–315.

[43] North, *The Norton History of Astronomy and Cosmology*, pp. 265–71; Shumaker, *The Occult Sciences in the Renaissance*, pp. 38, 44–8.

[44] Shumaker, *The Occult Sciences in the Renaissance*, pp. 16–27; North, *The Norton History of Astronomy and Cosmology*, p. 272. Lest the reader form the opinion that Pico was a rationalist skeptic, it should be pointed out that his main interest was in combining Hermetic magic and the Cabala into a sort of Christian gnosis, and that he objected to any claims that would restrict such a magical transformation. For an account of Pico's magical beliefs, see Yates, *Giordano Bruno and the Hermetic Tradition*, pp. 84–116.

was ignorant of both astronomy and astrology. In contrast, opponents of astrology included many, such as Luther, Calvin, and the Florentine radical Girolamo Savonarola (1452–1498), who assailed it from a religious perspective.[45] A very important exception was Luther's friend Melanchthon. He saw astrology as a clear illustration of divine providence, while the technical side of astronomy was simply a computational system subservient to astrology.[46]

Despite the ongoing debate about astrology's validity, the art itself remained stubbornly resistant to change. There was a lively but ultimately fruitless debate around the periphery regarding such issues as how to determine the divisions of the "houses" or positions of the planets with respect to the horizon at a given moment, with different nationalities promoting their respective champions. But teachings about the significance of the planets, the signs of the zodiac, the "aspects" or geocentric angles between the planets, and the houses continued to rely on authoritative texts, such as Ptolemy's *Tetrabiblos* and Albumasar's *Flores astrologici* (The Flowers of Astrology, 1488). Even the cosmological changes that were taking place around the turn of the seventeenth century had little effect on astrological theory, as demonstrated by the English nobleman Christopher Heydon's up-to-date fluid-filled heavens in his otherwise traditional *A Defence of Judiciall Astrologie* (1603).[47] Late seventeenth-century innovations in natural philosophy did, however, produce some interesting new twists on the subject of the terrestrial influences of heavenly bodies (see Rutkin, Chapter 23, this volume).

One of the most ambitious attempts to reform astrology came from Kepler (see Rutkin, Chapter 23, this volume). Kepler had read Pico carefully and agreed with much of what he had to say. But, as he wrote in the title of one of his works, one must be careful not to throw the baby out with the bath water. Kepler proposed a stripped-down astrology based on the new physical astronomy he was developing. He threw out all of the zodiacal signs on the grounds that there was no comprehensible way they could have any effect. What remained were the planetary qualities and their aspects, or angular configurations as seen from earth. These he tested empirically, using weather observations, and on the basis of these and his harmonic principles, he introduced some new aspects. The aspects were effective, he believed, because of the natural ability of souls (of humans, of animals, and even of

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[45] Shumaker, *The Occult Sciences in the Renaissance*, pp. 42–54.

[46] Kusukawa, *The Transformation of Natural Philosophy*, pp. 134–44.

[47] Heydon was replying to an attack by the Oxford mathematician John Chamber, whose views were conventionally Aristotelian. See Donahue, *The Dissolution of the Celestial Spheres*, pp. 69–72; Christopher Heydon, *A Defence of Judiciall Astrologie* (Cambridge, 1603), chap. 12, p. 302, and chap. 18, p. 370; and John Chamber, *Treatise Against Judicial Astrology* (London: John Harison, 1601), chap. 20, pp. 100–2. For controversies among astrologers, see North, *The Norton History of Astronomy and Cosmology*, pp. 259–61.

the earth as a whole) to perceive the angular relations of rays.[48] Despite Kepler's efforts, his new astrology failed to catch on. Astrologers were too firmly convinced of the real effects of the zodiacal signs to abandon them, and Kepler's physical notions proved as troublesome to the astrologers as they did to the astronomers.

In the sixteenth century, astrology, especially regarding the casting of horoscopes, was therefore not exactly intellectually disreputable but was certainly controversial. To make predictions involving political leaders could be embarrassing or even dangerous. However, making predictions was practically unavoidable for persons with astronomical skills, and a clever (and lucky) forecaster could profit substantially from it.

From the patrons' perspective, on the other hand, astrology was not simply a means of telling fortunes but also a way of understanding the cosmos and mankind's place in it. Such curiosity played a substantial role in supporting astronomical research and providing a market for accurate planetary tables and ephemerides. Without this support, the work of astronomers such as Kepler and Galileo would not have been possible, or at least would have taken a very different turn.

KEPLER'S REVOLUTION

Kepler, in addition to being one of the best-known astrologers of his day, was the first of a new breed of astronomers, a second-generation Copernican. At Tübingen he had studied under Maestlin, who was educated in the Lutheran astronomical tradition established by Melanchthon. However, unlike most in that tradition, Maestlin accepted Copernicus's physical claims, and although his textbook was conventionally geocentric, his students were encouraged to explore the physical and cosmological questions raised by Copernicus. Kepler took full advantage of this opportunity, arguing Copernican positions in public disputations.[49]

Although Kepler had intended to become a Lutheran minister, he accepted a post teaching mathematics at the Stiftsschule in Graz, Austria. While there, he began to ask questions that no one had previously raised, such as how the planets' distances from the sun were established and what, in the absence of real spheres and orbs, determines the planets' motions. After a remarkable flash of insight in the summer of 1595, he published some preliminary answers in his first major work, the *Mysterium cosmographicum* (The Cosmographical

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[48] Johannes Kepler, *Tertius interveniens* (Frankfurt: Tampach, 1610), in *Gesammelte Werke*, vol. 4, *Kleinere Schriften* (1941), p. 147; Judith V. Field, *Kepler's Geometrical Cosmology* (London: Athlone, 1988), pp. 127–42; and Field, "A Lutheran Astrologer: Johannes Kepler," *Archives for History of Exact Sciences*, 31 (1984), 189–273, which includes a translation of Kepler's *De fundamentis astrologiae certioribus* (Prague, 1602).

[49] Hellman, *The Comet of 1577*, pp. 137–44; and Caspar, *Kepler*, pp. 46–7.

Mystery, 1596). Kepler found that the five regular solids (tetrahedron, cube, octahedron, dodecahedron, and icosahedron), if arranged in the correct order, would fit between the orbits of the six planets with fair accuracy, and he argued that there must be a motive power in the sun that makes planets move faster when they are closer to it. This speed rule, which was an expression of qualitative observations and speculative physical reasoning, was later given a more precise mathematical form in Kepler's *Astronomia nova* (New Astronomy, 1609) and developed into what later came to be called Kepler's Second Law.[50]

The *Mysterium* was a direct attack on the conventional division of the sciences, in that Kepler argued (from scripture) that God created everything according to certain fundamental magnitudes, and that mathematics, being the science of magnitude, is fully qualified to establish physical truths. Although Kepler's views evolved with time, he later acknowledged that all of his later astronomical work had sprung from one or another chapter of that first book.[51]

When the *Mysterium cosmographicum* came to Tycho Brahe's attention, he recognized Kepler's brilliance but saw that he needed to learn the discipline of working with good observations. He invited Kepler to Prague (where Brahe had taken the post of imperial mathematician at the court of Rudolf II) to work with him on planetary theory. Meanwhile, the Counter-Reformation had made life difficult (and eventually impossible) for Lutherans in Graz, so Kepler accepted Brahe's offer, visiting Prague in the spring of 1600 and moving there with his family in October. Once there, he worked on studying Mars, which was a fortunate choice because the large eccentricity of its orbit made it more appreciably elliptical than the orbits of most other planets. The ensuing campaign (as Kepler described it) resulted in Kepler's greatest work, *Astronomia nova*, in which he continued his efforts to construct an astronomy based on physics.

Kepler's physics, however, was something quite different from what was taught in the schools: It involved invisible forces and powers that took on mathematical dimensions, and thus it brought the qualitative physics of the schools together with the quantitative precision of Brahe's observations. Kepler's theoretical method involved three distinct levels: The general physical principles were used to develop geometrical models of planetary motion, which were capable of generating planetary positions that could be checked against the observations. The discrepancies that were noted would then in

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[50] Caspar, *Kepler*, pp. 46–71; Johannes Kepler, *Mysterium cosmographicum: The Secret of the Universe*, trans. A. M. Duncan (New York: Abaris Books, 1981), chap. 14, pp. 155–9, and chaps. 20–22, pp. 197–221; William H. Donahue, "Kepler's Invention of the Second Planetary Law," *British Journal for the History of Science*, 27 (1994), 89–102; and E. J. Aiton, "Kepler's Second Law of Planetary Motion," *Isis*, 60 (1969), 75–90. The first published statement of this law is in Kepler's *Astronomia nova* (Heidelberg: Vögelin 1609), chap. 40, p. 193.

[51] Johannes Kepler, *Mysterium cosmographicum*, "Dedicatory Epistle" to the second edition, p. 39.

turn help Kepler revise the geometrical models. But any such revision would have to be done in conformity with the physical principles, whose operation would sometimes have to be reformulated to fit the new models. It was an entirely unprecedented way of building a theory; Kepler called it "astronomy without hypotheses," not because no assumptions were made but because each assumption was tested against the observations and against the restraints of physical possibility.[52]

In *Astronomia nova*, Kepler proposed a more exact version of the speed rule that he had originally stated in the *Mysterium cosmographicum* and showed that the orbit of Mars is elliptical. He later extended these principles to the other planets. But he still had no satisfactory expression for the relationship between orbital period and mean distance for multiple planets. He had come up with a provisional proportion in the *Mysterium cosmographicum*, but it failed to fit the observationally determined values. Nearly two decades after the publication of the *Mysterium*, in another flash of insight, Kepler came upon the accurate expression he had been seeking: In modern terms, it stated that the squares of the periods of the planets are proportional to the cubes of their distances from the sun. Kepler was unable to deduce this from physical principles as a general truth but saw it as an artificial proportionality that God had contrived by adjustment of the planets' sizes and densities.[53] Here, as in his elaborately deduced system of celestial harmonies in *Harmonices mundi* (Harmony of the World, 1618), Kepler was thinking along lines that seem strange to modern readers largely because the kinds of questions he was asking, such as what reasons God had for making things the way they are, do not seem meaningful in the context of modern science.

Kepler's astronomy was so radically different from anything that had preceded it, and so idiosyncratic, that he had difficulty convincing others of its truth. Although his introductory textbook, the *Epitome astronomiae Copernicanae* (Epitome of Copernican Astronomy, 1618–21), helped, it was the accuracy of his predictions that ultimately prevailed. Kepler's last great work, the *Tabulae Rudolphinae* (Rudolphine Tables, 1627), had been planned for nearly thirty years and was intended as a fitting tribute to his patron, Emperor Rudolf II, by whose appointment Kepler succeeded Brahe as imperial mathematician in 1601. These tables made the details of Kepler's planetary theories available to other astronomers, and comparisons of predictions, especially of

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[52] Bruce Stephenson, *Kepler's Physical Astronomy* (New York: Springer-Verlag, 1987; Princeton, N.J.: Princeton University Press, 1994); Kepler, *New Astronomy*, trans. Donahue; and Rhonda Maartens, *Kepler's Philosophy and the New Astronomy* (Princeton, N.J.: Princeton University Press, 2000).

[53] The first statement of this relationship appears in Kepler's *Harmonices mundi*, 5.3, translated in *Great Books of the Western World*, 54 vols. (Chicago: Encyclopaedia Britannica, 1955), vol. 16: *Ptolemy, Copernicus, Kepler*, p. 1020. Compare Field, *Kepler's Geometrical Cosmology*, pp. 142–63; and Bruce Stephenson, *The Music of the Heavens: Kepler's Harmonic Astronomy* (Princeton, N.J.: Princeton University Press, 1994), pp. 140–5.

a transit of Mercury across the sun in 1631 and a transit of Venus in 1639, clearly revealed Kepler's superiority.[54]

GALILEO

Kepler's older contemporary Galileo disagreed with him about almost everything except the physical reality of heliocentric astronomy. Galileo did not care much about the details of planetary motions and to his death continued to think of them as practically circular. His mathematical work dealt with terrestrial motions, though he extended some of his conclusion to the heavens. And aside from his mathematical treatment of motion (see Bertoloni Meli, Chapter 26, this volume), his most important work involved observations: the reinvention of the "optical tube" and transformation of this erstwhile toy into a scientific instrument, the telescope. These two aspects of Galileo's work, mathematical and empirical, were brought into harmony in his radically new approach to the understanding of nature.

Galileo had a thorough training in the natural philosophy of the schools. However, his main interest was in mathematics, especially practical mathematics. His earliest publications involved instruments, and he had a fondness for artisans, whose insights he often valued above those of his fellow academics. Galileo had not particularly cultivated astronomy, though by 1596 he was convinced of the truth of the Copernican system, and his observations of the new star (a galactic supernova) of 1604 show that he agreed with the astronomers' view that measurements of celestial phenomena could prevail over the arguments of the natural philosophers that the heavens must be unchangeable.[55]

Nevertheless, the publication that made Galileo famous showed none of this: It was a simple and straightforward account of his first observations with telescopes he had made himself, after hearing a report of the invention of such an optical device in Holland (see Bennett, Chapter 27, this volume). Galileo turned his new instrument, the design of which he had greatly improved, on the heavens, first observing the moon carefully and noting that its surface appeared to be rough and mountainous. Later, looking at Jupiter, he noticed what he thought were three small stars with which the planet was aligned. Subsequent observations showed that these stars, together with a fourth companion not seen at first, moved with Jupiter and appeared to be orbiting it. Observing the fixed stars, he found the Milky Way to be a vast field of tiny, hitherto unknown stars, and he noted that the telescope did not magnify the bodies of the stars, showing that their angular sizes were much less than

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[54] Wilbur Applebaum, "Keplerian Astronomy after Kepler: Researches and Problems," *History of Science*, 34 (1996), 462–4.

[55] Stillman Drake, *Galileo at Work* (Chicago: University of Chicago Press, 1978), chaps. 1–6, esp. pp. 106–8.

had been previously thought.[56] Although he did not draw any conclusions here, this observation countered one common objection to the Copernican arrangement: If the stars were at the huge distances implied by the lack of observable annual parallax, they would have to be almost unimaginably large.

These startling discoveries, published in the *Sidereus nuncius* (1610), illustrated most dramatically the power of observations to affect the plausibility of physical theories. Galileo's own claims were modest: He merely remarked that the discovery of Jupiter's moons removed one common objection to the Copernican system by showing that earth was not the only planet to have a satellite. But the observations spoke for themselves. Of course, there were some who doubted the reality of what appeared in the telescope, but within a year or two they had been discredited or convinced, especially when the observations were confirmed by independent observers in England, France, and other countries.[57] It was also clear that these new phenomena presented grave difficulties for traditional physics and cosmology. If the moon is rough and mountainous, like earth; if the stars, despite their brightness, are angularly tiny (and might therefore be very distant); if other planets have moons; and if (as Galileo soon announced) Venus goes through phases of illumination, like the moon, then how is the distinction between the changeable earth and the perfect, eternal heavens to be maintained?[58]

In the two decades following publication of his *Sidereus nuncius*, Galileo became a more outspoken proponent of the Copernican system. Although controversy about Jupiter's satellites was still raging, Galileo noticed that Venus was going through phases similar to the moon's, and he argued, in letters that were soon made public, that this phenomenon was inconsistent with the Ptolemaic arrangement of the planets but confirmed heliocentrism. He boldly raised the theological issues, repeating Cardinal Baronius's remark that "Scripture tells us how to go to heaven, not how the heavens go."[59] In a calculated act of rashness, he picked a lengthy fight with the Jesuits, who had been among the most receptive toward the new discoveries among the traditional philosophers. Shortly after his first telescopic observations, Galileo had found dark spots on the face of the sun, which he believed to be changing blotches on the sun's surface, evidence of alteration in the supposedly

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[56] Galileo Galilei, *Sidereus nuncius; or, the Sidereal Messenger*, trans. Albert Van Helden (Chicago: University of Chicago Press, 1989).

[57] For an account of the reception of the telescopic observations, see Albert Van Helden's conclusion to his translation of Galileo's *Sidereus nuncius*, pp. 90–113. Prominent skeptics who came to accept the observations were Christoph Clavius and Giovanni Antonio Magini (1555–1617), professor of mathematics at Bologna.

[58] Galileo, *Sidereus nuncius*, pp. 84, 104–6.

[59] Galileo announced the discovery of Venus's phases in December 1610 in letters to Giuliano de' Medici and Benedetto Castelli: see Van Helden's conclusion to *Sidereus nuncius*, pp. 105–9; see also Galileo Galilei, *Discoveries and Opinions of Galileo*, trans. Stillman Drake (Garden City, N.Y.: Doubleday Anchor Books, 1957), pp. 74–5. Galileo ascribed the epigram to Baronius in a marginal note to his "Letter to the Grand Duchess Christina," written in 1615 but not published until 1636: see Galileo, *Discoveries and Opinions*, p. 186.

unchanging heavens. The Jesuits at the Collegio Romano, although accepting the observations, set about explaining them as occultations by numerous small planets orbiting the sun, thus maintaining the heavens' incorruptibility, in accord with Aristotelian teaching. Such interpretations attempted to bend scholastic physical reasoning to accommodate Galileo's discoveries, dulling their revolutionary impact.

Galileo, in turn, believed that a mere revision of the qualitative physics of the schools would not do and proposed a "reading" of nature, after the humanist manner of reading and emulating classical texts, in which one would seek analogies rather than deductions.[60] A good example of this is his most famous work, the *Dialogo sopra i due massimi sistemi del mondo* (Dialogue on the Two Chief World Systems, 1632), a major part of which is devoted to a consideration of whether things in the heavens are like or unlike the things around us. It is conducted with experiments and examples that hold scholastic opinions up to ridicule.[61]

The effect of this "reading" on astronomy was profound. One would no longer begin, as Ptolemy had, with questions about the shape of the universe and the earth's place in it. Such questions were left open: Galileo emulated Socrates in stressing the importance of admitting ignorance as a first step toward learning.[62] The motion of the heavens was to be investigated not by drawing distinctions, refining definitions, and formulating hypotheses but by careful observation and analogical argument.

DESCARTES' COSMOLOGY

Although the French mathematician and philosopher René Descartes (1596–1650) did no significant work in astronomy, his cosmological theories shaped the way in which generations of astronomers viewed the world. In his *Principia philosophiae* (Principles of Philosophy, 1644) and in the posthumous *Le Monde* (The World, 1664),[63] he outlined a fanciful cosmogony in which a few very simple rules about collisions could lead to the formation of the universe as we see it (see Bertoloni Meli, Chapter 26, this volume). Variously sized chunks of matter are set variously in motion; and they begin to collide with one another and so are deflected into curved paths. This evolves into a large number of whirlpools or vortices, which serve to sort out the matter by size, and the more subtle matter is squeezed in toward the center and the very rapid motion it acquires generates light. Thus there is a star at the center of each vortex, with planets, comets, and so on, carried around as flotsam with the whirling fluid.[64]

Descartes' cosmology appealed to a generation of students raised on a modernization of school philosophy that had already accepted Brahe's fluid-filled heavens and Galileo's telescopic observations. It had the advantage of coherence and simplicity, and it kept religious questions mostly separate from scientific matters by creating a separate category for minds, souls, and spirits. In its superficial aspects, the vortex theory resembled the cosmic swirl of Hermetic neo-Platonist philosophers such as Telesio and Patrizi, a comparison to which Descartes strongly objected because he had banished the world soul and other animate agents. Nevertheless, the vortex model inevitably appealed to those who might otherwise have been drawn to the Hermeticists. Further, the vortex model suggested a way of explaining and predicting planetary motions that avoided the somewhat occult appearance of Kepler's invisible forces, powers, and planetary souls.[65]

THE SITUATION CIRCA 1650: THE RECEPTION OF KEPLER, GALILEO, AND DESCARTES

After the publication of Kepler's *Rudolphine Tables*, their superior accuracy made it only a matter of time before they came to be generally accepted. But tables do not themselves give planetary positions; they only provide the means for calculating them. And astronomers found the Rudolphine computations, especially the area rule, which related a planet's position on the orbit to the area of the sector it has traversed (for which there was no direct solution), cumbersome. So even those sympathetic to Kepler's melding of astronomy and physics found the idea of a geometrical approximation of the area rule attractive. Nevertheless, although a number of such shortcuts were

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[60] For an account of Galileo's polemics against the Jesuits, with references to source documents, see Pietro Redondi, *Galileo Heretic* (Princeton, N.J.: Princeton University Press, 1987), pp. 28–67. English translations of the central published works in this debate appear in Stillman Drake and C. D. O'Malley, trans., *The Controversy on the Comets of 1618* (Philadelphia: University of Pennsylvania Press, 1960).

[61] Galileo Galilei, *Dialogue on the Two Chief World Systems – Ptolemaic and Copernican*, trans. Stillman Drake (Berkeley: University of California Press, 1953), First Day, esp. pp. 60–101.

[62] Galileo, *Discoveries and Opinions*, pp. 256–8.

[63] *Le Monde* was written before the *Principia*, between 1629 and 1633, but Descartes decided not to publish it when he heard of Galileo's condemnation. Nevertheless, Descartes wryly claims that the world he is describing is imaginary.

[64] E. J. Aiton, *The Vortex Theory of Planetary Motions* (History of Science Library) (London: MacDonald, 1972), pp. 30–64.

[65] The resemblance was pointed out to Descartes by Isaac Beeckman (1588–1637). The exchange is in Beeckman, *Journal de 1604 à 1634; publié avec une introduction et des notes par C. de Waard*, 4 vols. (La Haye: Martinus Nijhoff, 1939–53), 1: 260–1 and 360–1; 4: 49–51. Natural philosophers who mingled Cartesian with Hermetic ideas include Henry More (1614–1687), Daniel Lipstorp (1631–1684), and Athanasius Kircher (1601–1680). Accounts of at least four other contemporary authors who saw Cartesian and Hermetic ideas as congenial are provided by P. M. Rattansi, "The Intellectual Origins of the Royal Society," *Notes and Records of the Royal Society*, 23 (1968), 129–43, at pp. 131–6; and Charles Webster, "Henry Power's Experimental Philosophy," *Ambix*, 14 (1967), 150–78, at p. 153. A full account of mingled Cartesian theories is found in Donahue, *The Dissolution of the Celestial Spheres*, pp. 137–42, 287–92.

developed, the two fundamentally Keplerian ideas of nonuniform motion and noncircular orbits had become firmly established by mid-century.[66]

There was less agreement about the physical causes of the motions, Kepler had opened the debate in his *Astronomia Nova* (1609), developing a theory in which the rotating sun sweeps the planets around by means of quasi-corporeal "fibers," while the planets are moved toward and away from the sun by magnetic attractions and repulsions. Some astronomers, especially early in the century, were as a matter of principle unwilling to accept such physical explanations in astronomy.[67] However, by 1650 there were at least six competent mathematicians and astronomers in Germany, France, the Low Countries, and England who fully endorsed and expounded Kepler's theories in published works or in other ways.[68] Others mingled Keplerian ideas with Galilean or Cartesian physics. One difficulty with Kepler's physical ideas was that he believed, along with Aristotle, that motions would not continue without some moving cause. Those who accepted Galileo's and Descartes' arguments that things in uniform rectilinear motion tend to keep moving by themselves were faced with the challenge of finding a replacement for Kepler's tangential forces and magnetic attractions and repulsions. Suggestions came from the Dutch Cartesian mathematician Christiaan Huygens (1629–1695); Gilles Personne de Roberval (1602–1675), professor of mathematics at the University of Paris and also a Cartesian; the English natural philosophers Robert Hooke (1635–1703) and Thomas Hobbes (1588–1679); the Italian physiologist and mathematician Giovanni Alfonso Borelli (1609–1679); and others. The English mathematician and astronomer Jeremiah Horrox (1619–1641), though a confirmed Keplerian, noticed that Jupiter and Saturn appeared to be interacting, and this suggested that the planets might be attracting each other. Nevertheless, only one of these theorists, Borelli, came up with an alternative physical account that could generate planetary positions before the publication of Newton's *Principia*.[69]

The main alternative to Kepler's theories was their geometrical reworking by the French astronomer Ismael Bouillau (1605–1694). He set out systematically to refute Kepler's physics, replacing it with an elaborately argued theory that, in essence, ascribes to each planet a natural form that governs its motion, that form being the section of a cone, around the axis of which the planet moves uniformly. Bouillau's astronomy was well received, especially in England, and was commended by Newton. However, at least part of its success must be attributed to the substitution of an old-style equant for Kepler's cumbersome area calculation. Astronomers continued to use whatever system or combination of systems appealed to them, and in principle thought of them as more or less equivalent. However, in 1670, Nicolaus Mercator (ca. 1619–1687), a Danish astronomer living in England, took up the question of the accuracy of the geometrical methods. He showed that all such methods amounted to a solution that Kepler had tried and rejected, which involved uniform angular motion around the empty focus of the ellipse. In Mercator's view, Kepler's ellipses and his area rule must stand or fall together. This proved to be a turning point in the further history of Kepler's planetary theories.[70]

With regard to the physical system into which these planetary orbits fit, Galileo's heresy trial in 1633 changed everything. The question of heliocentrism versus geocentrism (in Catholic countries at least) ceased to be a matter of physics and became a matter of faith. This had the effect of stifling debate and encouraged the adoption of the Tychonic system as a prudent compromise. Influential Jesuits such as Christoph Scheiner (1573–1650), professor of mathematics at the University of Ingolstadt, favored the Tychonic system as early as 1612, and after Galileo's condemnation it was universally espoused by the Jesuits. As late as 1728, the Italian Jesuit Francesco Bianchini (1662–1729) described it as the commonly accepted system. In Lutheran Germany and Anglican England, this arrangement had few adherents – new physical and cosmological ideas had made the idea of a moving earth much less problematic.[71]

The increasing acceptance of the heliocentric (or semiheliocentric) system raised another question: the dimensions of the planetary system and the corresponding distance of the stars. The Copernican arrangement gave relative distances of the planets from the sun but did not relate those distances to familiar terrestrial units. Such a calibration would require the measurement of the diurnal parallax of the sun or a planet. (Diurnal parallax is the parallax that results from our being on the earth's surface rather than at its center.) Early attempts to find a parallax, such as those by Brahe and Kepler, produced mixed but ultimately negative results, which could nevertheless be useful in determining a lower limit for the distance. On the basis of the failure to find any parallax for Mars at opposition (when it is closest to earth), Kepler estimated the solar parallax as no more than one arc minute, making the sun's distance at least 22,000,000 km, about three times the generally accepted

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[66] Applebaum, "Keplerian Astronomy," pp. 484–5.

[67] Ibid., p. 459.

[68] Donahue, *The Dissolution of the Celestial Spheres*, pp. 249–50 (citing Noel Duret, Johannes Hainlin, Pierre Herigone, Johannes Phocylides Holwarda, and Jeremiah Horrox), and p. 293 (citing Johannes Hevelius).

[69] Aiton, *The Vortex Theory of Planetary Motions*, pp. 90–8, 126–7; and Alexandre Koyré, *The Astronomical Revolution: Copernicus, Kepler, Borelli* (New York: Dover, 1992).

[70] Aiton, *The Vortex Theory of Planetary Motions*, p. 91; Ismael Bullialdus [Ismael Boullian], *Astronomia Philolaica* (Paris: S. Piget, 1645), bk. 1, chaps. 12–14, pp. 21–37; North, *The Norton History of Astronomy and Cosmology*, pp. 356–9; Applebaum, "Keplerian Astronomy," pp. 470–1; and Curtis A. Wilson, "From Kepler's Laws, So-Called, to Universal Gravitation: Empirical Factors," *Archive for History of Exact Sciences*, 6 (1970), 106–32.

[71] Christine Schofield, "The Tychonic and Semi-Tychonic World Systems," in *The General History of Astronomy*, vol. 2A, ed. René Taton and Curtis Wilson (Cambridge: Cambridge University Press, 1989), pp. 42–4.

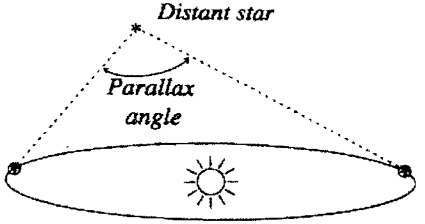

Figure 24.4. Annual parallax.

Ptolemaic distance. In the next half-century, a number of attempts were made (based on Keplerian speculations and unreliable observations) to find the distance more accurately. The resulting distances were all substantially greater than Kepler's lower limit. However, the first reliable measurements were made in 1672, applying the newly developed micrometer to the opposition of Mars in that year. Parallaxes measured by the English Astronomer Royal John Flamsteed (1646–1719) and the French astronomer Jean Richer (1630–1696) yielded distances of 132,000,000 km and 110,000,000 km, respectively. (The modern value is about 150,000,000 km.)[72]

This considerable enlargement of the planetary system made the apparent absence of annual parallax of the fixed stars (see Figure 24.4) all the more surprising and prompted attempts to measure it. Hooke claimed positive results in observations of the star Gamma Draconis in the 1670s using a telescope built into his house. However, his conclusions met with a mixed reception, and similar observations after 1692 by Danish astronomer Ole Römer (1644–1710) produced a negative result. Reliable measurements of stellar parallax, which is less than one arc second even for the closest stars (other than the sun), was beyond the capability of seventeenth-century instruments and had to await the discovery of the aberration of light by English astronomer James Bradley (1693–1762) in 1729 and of the proper motions of the stars, first proposed by English astronomer and natural philosopher Edmund Halley (1656–1743) in 1618.[73]

NOVAE, VARIABLE STARS, AND THE DEVELOPMENT OF STELLAR ASTRONOMY

Although the cosmological changes implicit in the works of Galileo and Descartes did not have an immediate effect on planetary theory, they helped inspire a new interest in the stars. Even those who still held that the stars swirl around the earth once a day no longer felt the need to restrain them to a single spherical surface, and it was becoming common to think of the stars as being like the sun.[74] This raised questions about the distribution and distances of the stars that encouraged more careful attention to them. Furthermore, the telescope had revealed the existence of a great many previously unknown stars, so there was more to look at and much mapping to be done.

But the greatest spur to the study of the stellar region was the possibility of discovering a "new star" – that is, a nova (or supernova) such as the one that had so startlingly appeared in 1572. This nova, which at its peak brightness was visible even during the day, was studied by Brahe and many other astronomers, the prevailing opinion being that it was a real star, or possibly a celestial comet, and not an atmospheric phenomenon. The existence of this nova was very troublesome to those who followed Aristotle in believing the heavens to be eternal and unchanging.[75]

The question naturally arose whether any new stars had ever been previously reported and whether a more careful search would find more of them. A historical search turned up a few candidates, and observers found a new incentive for remapping the heavens in order to be sure of the stars that were already there. Brahe and Dutch cartographer and instrument maker Willem Blaeu (1571–1638) responded to this substantial challenge. The search for new novae was also successful: Less prominent new stars were found by the Frisian astronomer David Fabricius (1564–1617) in 1596 and by Kepler and others in 1600 (and perhaps also in 1602), and a much brighter one (another supernova) was observed at the end of 1603 and through much of 1604.[76]

Over the next three decades, there were a few doubtful or spurious sightings (including one that was in fact the Great Andromeda Galaxy), and then a reliable one in 1638 by the Frisian astronomer Johannes Phocylides Holwarda (1618–1651). In 1640, while his book reporting the discovery was in press, Holwarda was astonished to discover that the star had reappeared. This was reported in a hastily added appendix. Subsequently, careful study of the star by the Danzig astronomer Johannes Hevelius (1611–1687) identified it as probably the same as Fabricius's "nova" of 1596, as well as the star Omicron Ceti in Blaeu's listing. After further observation and reference to earlier accounts, Bouillau found that the fluctuations were periodic, with a period of about 333 days, and he successfully predicted future maxima. He also proposed a physical explanation involving a lucid region of the star that was periodically displayed by the star's rotation.[77]

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[72] Albert Van Helden, "The Telescope and Cosmic Dimensions," *General History of Astronomy*, 2A: 108–17; and Van Helden, *Measuring the Universe: Cosmic Dimensions from Aristarchus to Halley* (Chicago: University of Chicago Press, 1985), pp. 105–47.

[73] Schofield, "The Tychonic and Semi-Tychonic World Systems," p. 41. Römer, it should be noted, was a proponent of the Tychonic planetary arrangement, and thus saw a small parallax as favoring Tycho over Copernicus. For aberration and proper motions, see North, *History of Astronomy and Cosmology*, pp. 383, 395.

[74] Donahue, *The Dissolution of the Celestial Spheres*, pp. 298–300.

[75] Hellman, *The Comet of 1577*, pp. 111–17.

[76] This paragraph as well as the following account of variable stars is based on Michael A. Hoskin, "Novae and Variables from Tycho to Bullialdus," *Sudhoffs Archiv für Geschichte der Medizin und der Naturwissenschaften*, 61 (1977), 195–204.

[77] Ismael Bullialdus, *Ad Astronomos Monita Duo* (Paris, 1667).

The discovery of the periodicity of Omicron Ceti (or Mira, "the Wonder," as it was called) initiated a widespread interest in the stars that marked the beginning of stellar astronomy as a separate field of study. Thus there were many reports of variable stars in the next few years, and by the end of the century astronomers were beginning to suspect that even the old novae of Brahe and Kepler were really variable stars with periods of many years or even centuries.

NEWTON

The physical theories of Newton had a profound influence on planetary astronomy for centuries to come, establishing the ground rules for the construction of planetary orbits. Nevertheless, his direct contributions to astronomy were few. He made his scientific debut before the Royal Society in 1672 with a reflecting telescope that he had designed and built, but this was merely a by-product of his interest in optical theory. Newton later observed the comet of 1680–1 and the 1682 appearance of what came to be known as Halley's Comet, observations that played an important role in the development of his account of orbital motions in his most celebrated work, *Philosophiae Naturalis Principia Mathematica*, usually called simply *Principia.*[78] And between the first edition of *Principia* and the 1713 second edition, Newton developed a lunar theory, published in 1702.

The *Principia* itself, though not primarily an astronomical work, promised to transform planetary astronomy by providing a physical account of all planetary motions. In this, Newton nearly reached Kepler's goal of creating an "astronomy without hypotheses" to be based on physical forces. Much of Book III of *Principia* is devoted to explaining the various lunar wobbles and finding the orbits of comets. Furthermore, the theory of universal gravitation had implications that led to speculation about, and study of, the distribution of the stars.

When it came to the details, however, Newton's mathematics was not up to the task. It was not until the middle of the eighteenth century that gravitationally based lunar theories began to produce usable numbers. Meanwhile, there was a practical demand for a more accurate lunar theory. If the moon's position could be known accurately for any given time, it would become in effect a universal clock, allowing navigators to determine their longitude by comparing the moon's observed position among the stars with local time.

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[78] For general information about Newton's life and works, see Richard S. Westfall, *Never at Rest: A Biography of Isaac Newton* (Cambridge: Cambridge University Press, 1980). An account of the telescope appears at pp. 232–40, and Newton's comet observations are at pp. 391–7. Newton's knowledge of contemporary astronomy is described in Wilson, "From Kepler's Laws, So-called, to Universal Gravitation," sec. 8, pp. 89–170. The importance of Newton's observations of Halley's Comet is argued in Nicholas Kollerstrom, "The Path of Halley's Comet, and Newton's Late Apprehension of the Law of Gravity," *Annals of Science*, 56 (1999), 331–56.

The determination of longitude was the most pressing practical scientific problem of the day, for the solution of which the British Parliament in 1714 offered a huge reward. By this time, the commercial importance of accurate astronomical measurements had long been evident, having led to the foundation of the Paris Observatory in the 1660s and the Greenwich Observatory in 1675.

It was partly in response to the longitude problem that Newton wrote *Theory of the Moon's Motion* (1702). This curious little work, first published as an addendum to David Gregory's *Astronomiae elementa* (Elements of Astronomy, 1702), was a purely kinematic and geometric theory, based on Horrox's modification of Kepler's lunar theory, using devices that dated back to ancient Greece. In fact, it was probably the last serious astronomical work to make use of the Ptolemaic epicycle.

Another reason for creating this theory was to establish accurately the various components of the moon's complicated orbit in order to begin the job of explaining it physically. A new version of the lunar theory, heavily disguised and with some corrections, but still recognizable, was included in the 1713 edition of *Principia.* In this revision, Newton attempted to give a physical explanation of as many of the equations as he could, but he finally had to abandon all pretense of a dynamic account – writing, "The computation of this motion is difficult," and continuing with a purely geometrical and kinematic description of the final inequality.[79]

The 1702 lunar theory, retrograde though it was, was remarkably influential. Its basic form (with various adjustments to the parameters) was used in publications by at least a dozen astronomers before 1750, many of whom used the theory to compute lunar tables and ephemerides. The theory fell into disuse after 1753 as a result of the publication of gravitationally based lunar theories by German cartographer and astronomer Tobias Mayer (1723–1762) and Swiss mathematician Leonhard Euler (1707–1783).[80]

The enormous significance of Newton's work for astronomy lay not in his direct contributions but in the way his establishment of universal gravitation and mathematical methods created a new context in which astronomical problems were investigated. In planetary astronomy, the most important question became how to apply gravitational theory to explain ever more subtle anomalies. In stellar astronomy, the great distance of the stars, which had once seemed such an implausible concomitant to the heliocentric planetary

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[79] Isaac Newton, *The Principia*, trans. I. Bernard Cohen and Anne Whitman (Berkeley: University of California Press, 1999), bk. 3, prop. 35, Scholium, pp. 869–74. The epicycle is described at pp. 871–2, and the quoted phrase is at p. 873. The complete text of the *Theory of the Moon's Motion*, with a complete commentary and assessment of its importance, is in Nicholas Kollerstrom, *Newton's Forgotten Lunar Theory: His Contribution to the Quest for Longitude* (Santa Fe, N.M.: Green Lion Press, 2000). An account of the circumstances of the composition and publication of the lunar theory is in I. Bernard Cohen, *Isaac Newton's Theory of the Moon's Motion (1702), with a Bibliographical and Historical Introduction* (New York: Neale Watson, 1975).

[80] Kollerstrom, *Newton's Forgotten Lunar Theory*, pp. 205–23.

arrangement, was now seen as a necessary consequence of universal gravitation, a means of keeping the universe from collapsing on itself. Thus, the attempt to measure the annual stellar parallax continued, but on a much more refined scale. The stars themselves were now seen as independent bodies, possibly moving through space. (The existence of independent proper motions was soon confirmed, initially by Halley in 1718 and later by French astronomer Jacques Cassini II (1677–1756) in 1738 using more precise measurements.[81]) Newton's accomplishment was the completion of Kepler's quest to turn astronomy into physics, and, in the course of this, the recasting of physics as mathematics.

For observational astronomy, by the end of the seventeenth century it was clear that the current set of problems often required a degree of precision beyond the reach of individual investigators. The Royal Greenwich Observatory, in particular, became the center of a small instrument-making industry that supplied observatories all over Europe.[82] Although there was still room for the amateur observer (as indeed there is today), much of the most important astronomical observation would henceforth have to be done in government-supported institutions.

CONCLUSION

During the sixteenth and seventeenth centuries, astronomy had evolved from a mathematical discipline (with an observational component) into a true physical science. Initially, this transformation was the result of a change in context. Because of developments in philosophy and theology, especially the trend (exemplified by the philosophy of Descartes) toward banishing minds and souls from the physical universe, the heavens came to be seen as not radically distinct from the earth. Planetary astronomy accordingly changed from a purely descriptive geometrical construction into an ongoing project in gravitational dynamics involving physical bodies. Although the geometrical constructs were still widely used, Kepler's challenge of finding the true, physical orbits of the planets and their causes became recognized as the chief goal of planetary theory.

At the same time, stellar astronomy, which had previously consisted of charting the supposedly unchanging positions and magnitudes of the fixed stars, had become a discipline in its own right. Again, it was the Cartesian-Galileian-Newtonian context that helped transform the stars from points of light upon a spherical surface into great luminous bodies in an indefinitely large space. Good luck, in the form of several very prominent "new" stars that

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[81] North, *History of Astronomy and Cosmology*, chap. 14, esp. pp. 383–4 and 395–6.
[82] Ibid., p. 381.

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appeared in the late sixteenth and seventeenth centuries, also drew attention to the stellar region as worthy of more careful study.

The rise of stellar astronomy, as well as the increasing demands of planetary astronomy for better data, proved a powerful incentive for the development of better instruments (see Bennett, Chapter 27, this volume). Instrument making had always played an important role in astronomy, but the invention of the telescope, and the discoveries it immediately revealed, showed dramatically what instrumental innovation could achieve. The result was an enlarged and often publicly supported instrument-making industry that was required to produce devices whose precision and elaborate construction far surpassed that of earlier instruments. And as the use of the new instruments became more technically demanding, observational astronomy became a specialty in its own right.

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[81] North, *History of Astronomy and Cosmology*, chap. 14, esp. pp. 383–4 and 395–6.

[82] Ibid., p. 381.