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(b. Weil der Stadt, Germany, 27 December 1571; d. Regensburg, Germany, 15 November 1630)

astronomy, physics.

Although Kepler is remembered today chiefly for his three laws of planetary motion, these were but three elements in his much broader search for cosmic harmonies and a celestial physics. With the exception of Rheticus, Kepler became the first enthusiastic Copernican after Copernicus himself; he found an astronomy whose clumsy geocentric or heliostatic planetary mechanisms typically erred by several degrees and he left it with a unified and physically motivated heliocentric system nearly 100 times more accurate.

When Kepler was twenty-five and much occupied with astrology, he compared the members of his family with their horoscopes.¹ His grandfather Sebald, mayor of Weil in 1571, when Kepler was born, was “quick-tempered and obstinate.” His grandmother was “clever, deceitful, blazing with hatred, the queen of busybodies.” His father, Heinrich, was described as “criminally inclined, quarrelsome, liable to a bad end” and destined for a “marriage fraught with strife.” When Kepler was three years old, his father joined a group of mercenary soldiers to fight the Protestant uprising in Holland, thereby disgracing his family. Soon after his return in 1576, he again joined the Belgian military service for a few years; and in 1588 he abandoned his family forever.

Although Kepler describes his mother, the former Katharina Guldenmann, as “thin, garrulous, and bad-tempered,” he adds that “treated shabbily, she could not overcome the inhumanity of her husband.” Katharina showed her impressionable son the great comet of 1577. Later, Kepler spent many months between 1617 and 1620 preparing a legal defense when his aged but meddling mother was accused of and tried for witchcraft.

Kepler first attended the German Schreibschule in Leonberg, where his family had moved in 1576; shortly after, he transferred to the Latin school, there laying the foundation for the complex Latin style displayed in his later writings. In 1584 he entered the Adelberg monastery school; and two years later enrolled at Maulbronn, one of the preparatory schools for the University of Tübingen. In October 1587 Kepler formally matriculated at Tübingen; but because no room was available at the Stift, the seminary where, as a scholarship student supported by the duke of Württemberg, he was expected to lodge, he continued at Maulbronn for another two years. On 25 September 1588 he passed the baccalaureate examination at Tübingen, although he did not actually take up residence there until the following year.

At Tübingen, Kepler's thought was profoundly influenced by Michael Maestlin, the astronomy professor. Maestlin knew Copernican astronomy well; the 1543 *De revolutionibus* he owned is probably the most thoroughly annotated copy extant; he edited the 1571 edition of the *Prutenicae tabulae*, and he used them to compute his own *Ephemerides*. Although Maestlin was at best a very cautious Copernican, he planted the seed that with Kepler later blossomed into a full Copernicanism. The ground was fertile. Kepler's quarterly grades at the university, still preserved, show him as a “straight A” student; and when he applied for a scholarship renewal at Tübingen, the senate noted that he had “such a superior and magnificent mind that something special may be expected of him.” Nevertheless, Kepler himself wrote concerning the science and mathematics of his university curriculum that “these were the prescribed studies, and nothing indicated to me a particular bent for astronomy.”²

On 11 August 1591 Kepler received his master's degree from Tübingen and thereupon entered the theological course. Halfway through his third and last year, however, an event occurred that completely altered the direction of his life. Georgius Stadius, teacher of mathematics at the Lutheran school in Graz, died; and the local authorities asked Tübingen for a replacement. Kepler was chosen; and although he protested abandoning his intention to become a clergyman, he set out on the career destined to immortalize his name.

Graz and the *Mysterium Cosmographicum* . On 11 April 1594, the twenty-two-year-old Kepler arrived in southern Austria to take up his duties as teacher and as provincial mathematician. In the first year he had few pupils in mathematical astronomy and in the second year none, so he was asked to teach Vergil and rhetoric as well as arithmetic. But the young Kepler made his mark in another way; soon after coming to Graz, he issued a calendar and prognostication for 1595, which contained predictions of bitter cold, peasant uprisings, and invasions by the Turks. All were fulfilled, to the great enhancement of his local reputation. Five more calendars followed in annual succession, and later in Prague he issued prognostications for 1602 to 1606. These ephemeral items are now extremely rare, some surviving in unique copies; and all the copies of nearly half the editions are totally lost.

Kepler's personal reaction to astrology was mixed. He rejected most of the commonly accepted rules, and he repeatedly referred to astrology as the foolish little daughter of respectable astronomy. In *De fundamentis astrologiae certioribus* (1601) he wrote: "If astrologers sometimes do tell the truth, it ought to be attributed to luck."³ Nevertheless, his profound feeling for the harmony of the universe included a belief in a powerful concord between the cosmos and the individual. These views found their fullest development in the *Harmonice mundi*. Furthermore, his astrological opinions continually provided welcome supplementary justification for his office as imperial mathematician. At least 800 horoscopes are still preserved in his manuscript legacy. Included are many for himself; if we are to believe the deduced time of his conception (16 May 1571, at 4:37 A.M. on his parents' wedding night), then he was a seven-month baby.

Concerning the calendars, Kepler later wrote: "Because astrology has no language other than that used by common man, so the common man will not understand otherwise, knowing nothing of the generalities of abstractions and seeing only the concrete, will often praise a calendar in an accidental case that the author never intended or blame it when the weather doesn't come as he expects: so much trouble have I brought upon myself, that I finally have given up writing calendars."⁴ Nevertheless, Kepler later produced a series from 1618 to 1624, excusing himself with the remark that when his salary was in arrears, writing calendars was better than begging.

Meanwhile, just over a year after his arrival in Graz, Kepler's fertile imagination hit upon what he believed to be the secret key to the universe. His own account, here greatly abridged, appears in the introduction to the resulting work, the *Mysterium cosmographicum* of 1596.

When I was studying under the distinguished Michael Maestlin at Tübingen six years ago, seeing the many inconveniences of the commonly accepted theory of the universe, I became so delighted with Copernicus, whom Maestlin often mentioned in his lectures, that I often defended his opinions in the students' debates about physics. I even wrote a painstaking disputation about the first motion, maintaining that it happens because of the rotation of the earth. I have by degrees—partly out of hearing Maestlin, partly by myself—collected all the advantages that Copernicus has over Ptolemy. At last in the year 1595 in Graz when I had an intermission in my lectures, I pondered on this subject with the whole energy of my mind. And there were three things above all for which I sought the causes as to why it was this way and not another—the number, the dimensions, and the motions of the orbs.⁵

After describing several false attempts, Kepler continues:

Almost the whole summer was lost with this agonizing labor. At last on a quite trifling occasion I came near the truth. I believe Divine Providence intervened so that by chance I found what I could never obtain by my own efforts. I believe this all the more because I have constantly prayed to God that I might succeed if what Copernicus had said was true. Thus it happened 19 July 1595, as I was showing in my class how the great conjunctions [of Saturn and Jupiter] occur successively eight zodiacal signs later, and how they gradually pass from one trine to another, that I inscribed within a circle many triangles, or quasi-triangles such that the end of one was the beginning of the next. In this manner a smaller circle was outlined by the points where the line of the triangles crossed each other [see Fig. 1].

The proportion between the circles struck Kepler's eye as almost identical with that between Saturn and Jupiter, and he immediately initiated a vain search for similar geometrical relations.

And then again it struck me: why have plane figures among three-dimensional orbits? Behold, reader, the invention and whole substance of this little book! In memory of the event, I am writing down for you the sentence in the words from that moment of conception: The earth's orbit is the measure of all things; circumscribe around it a dodecahedron, and the circle containing this will be Mars; circumscribe around Mars a tetrahedron, and the circle containing this will be Jupiter; circumscribe around Jupiter a cube, and the circle containing this will be Saturn. Now inscribe within the earth an icosahedron, and the circle contained in it will be Venus; inscribe within Venus an octahedron, and the circle contained in it will be Mercury. You now have the reason for the number of planets.

Kepler of course based his argument on the fact that there are five and only five regular polyhedrons.

This was the occasion and success of my labors. And how intense was my pleasure from this discovery can never be expressed in words. I no longer regretted the time wasted. Day and night I was consumed by the computing, to see whether this idea would agree with the Copernican orbits, or if my joy would be carried away by the wind. Within a few days everything worked, and I watched as one body after another fit precisely into its place among the planets.

Astonishingly, Kepler's scheme works with fair accuracy when space is allowed for the eccentricities of the planetary paths. The numbers are given in Table I. Kepler was obliged to compromise the elegance of his system by adopting the second value for Mercury, which is the radius of a sphere inscribed in the square formed by the edges of the octahedron, rather than in the octahedron itself. With this concession, everything fits within 5 percent—except Jupiter, at which "no one will wonder, considering such a great distance."

Table 1. Ratios of adjacent planetary orbits

(assuming the innermost part of the outer orbit to be 1000).

Planet Saturn Intervening Regular Solid Computed by Kepler From Copernicus

Jupiter	Cube	577	635
Mars	Tetrahedron	333	333
Earth	Dodecahedron	795	757
Venus	Icosahedron	795	794
Mercury	Octahedron	577 Or 707	723

Quixotic or chimerical as Kepler's polyhedrons may appear today, we must remember the revolutionary context in which they were proposed. The *Mysterium cosmographicum* was essentially the first unabashedly Copernican treatise since *De revolutionibus* itself; without a sun-centered universe, the entire rationale of his book would have collapsed. Moreover, even the inquiry about the basic causes for the number and motions was itself a novel break with the medieval tradition, which considered the "naturalness" of the universe sufficient reason. For Kepler, the theologian-cosmologist, nothing was more reasonable than to search for the architectonic principles of creation. "I wanted to become a theologian," he wrote to Maestlin in 1595; "for a long time I was restless. Now, however, behold how through my effort God is being celebrated in astronomy."⁶

Furthermore, Kepler demanded to know how God the architect had set the universe in motion. He recognized that although in Copernicus' system the sun was near the center, it played no physical role. Kepler argued that the sun's centrality was essential, for the sun itself must provide the driving force to keep the

planets in motion. This physical reasoning, which characterizes Kepler's astronomy, makes its appearance in the latter part of the *Mysterium cosmographicum*. After announcing his celebrated nest of spheres and regular solids, which to him explained the spacing of the planets, he turned to the search for the basic cause of the regularities in the periods.

Kepler knew that the more distant a planet was from the sun, the longer its period—indeed, this was one of the most important regularities of the heliocentric system, already noted by Copernicus, that had appealed so strongly to Kepler's aesthetic sense. Kepler believed that the longer periods directly reflected the diminution with distance of the sun's driving force. Thus, he sought to relate the planetary periods (p_1, p_2, \dots) to the intervals between the planets; with this step he had gone from the heliostatic scheme of Copernicus to a physically heliocentric system. After several trials he formulated a relation for the ratios of the distances equivalent to $(p_1/p_2)^{1/2}$ rather than the correct $(p_1/p_2)^{2/3}$, but this gave a sufficiently satisfactory first result, as seen in Table II.

TABLE II. Mean ratios of the planetary orbits.

Planets	Computed by Kepler From Copernicus	
Jupiter/Saturn	574	572
Mars/Jupiter	274	290
Earth/Mars	694	658
Venus/Earth	762	719
Mercury/Venus	563	500

Although the principal idea of the *Mysterium cosmographicum* was erroneous, Kepler established himself as the first, and until Descartes the only, scientist to demand physical explanations for celestial phenomena. Seldom in history has so wrong a book been so seminal in directing the future course of science.

As an impecunious young instructor, Kepler submitted his manuscript to the scrutiny of Tübingen University because his publisher would go ahead only with the approval of the university authorities. Without dissent the entire senate endorsed the publication of Kepler's militantly pro-Copernican treatise, but they requested that he explain his discovery and also Copernicus' hypotheses in a clearer and more popular style. In the actual publication the reasons for abandoning the Ptolemaic in favor of the [Copernican system](#) are set forth in the first chapter with remarkable lucidity. J. L. E. Dreyer has noted that "it is difficult to see how anyone could read this chapter and still remain an adherent of the [Ptolemaic system](#)."⁷

The Tübingen senate also recommended that Kepler delete his "discussion of the Holy Writ in several theses." This Kepler did, but he later incorporated his arguments into the introduction of his *Astronomianova*:

But now the Sacred Scriptures, speaking to men of vulgar matters (in which they were not intended to instruct men) after the manner of men, that so they might be understood by men, do use such expressions as are granted by all. . . . What wonder is it

then, if the scripture speaks according to man's apprehension, at such time when the truth of things doth dissent from the conception [of] all men?

This version, from Thomas Salusbury in 1661, is a part of the first and only seventeenth-century translation of any of Kepler's works. The passage was also repeatedly reprinted as an appendix to the Latin translation of Galileo's *Dialogo*. In the words of Edward Rosen, "Kepler's clarion call, trumpeted to receptive ears, echoed and reechoed down the corridors of the seventeenth century and thereafter. It demonstrated how unswerving allegiance to the scientific quest for truth could be combined in one and the same person with unwavering loyalty to religious tradition: accept the authority of the Bible in questions of morality, but do not regard it as the final work in science."⁸

As soon as the *Mysterium cosmographicum* arrived from the printer early in 1597, Kepler sent copies to various scholars. By return courier Galileo sent a few civil sentences saying that he had as yet read only the preface. Kepler, unsatisfied, sent a spirited reply urging Galileo to "believe and step forth." [Tycho Brahe](#) offered a detailed critique, calling the nest of inscribed spheres and polyhedrons a clever and polished speculation. Kepler's book, notwithstanding its faults, had thrust him into the front rank of astronomers. Looking back as a man of fifty, Kepler remarked that the direction of his entire life and work took its departure from this little book.

Kepler had entitled his book *Prodromus dissertationum cosmographicarum continens mysterium cosmographicum . . .* ("A Precursor to Cosmographical Treatises . . ."), thus implying a continuation. Following the publication of his first book, Kepler plunged into studies for not one but four cosmological treatises. His interests ranged from the observation of lunar and solar eclipses—he first found the so-called annual equation of the moon's motion—to chronology and harmony. By 1599 he had outlined the plan for one of his principal works, the *Harmonice mundi*. Yet fate, in the form of the gathering storm of the Counterreformation, once more diverted the course of Kepler's life; and the *Harmonice* was not completed until 1619.

Meanwhile, another discovery molded Kepler's life: the eldest daughter of a wealthy mill owner, Barbara Müller, had "set his heart on fire ." Two years younger than Kepler, she had been widowed twice. Early in 1596 Kepler sought her hand, but his seven-month absence on a trip to Tübingen almost scuttled the courtship. The wedding took place 27 April 1597, under ominous constellations, as Kepler noted in his diary. The initial happiness of his marriage gradually dissolved as he realized that his wife understood nothing of his work—"fat, confused, and simpleminded" was Kepler's later description of her. The early death of his first two children grieved him deeply. His wife's fortune was tied into estates, so it was difficult to transfer their assets when the Lutheran Kepler was forced to abandon Catholic Graz and move to Prague. There Kepler was eventually to find an exhilarating freedom, but his wife, out of her depth in court circles, found only homesickness and monetary worries.

Prague and the Astronomianova. The numerous Protestants in Graz remained unmolested by their Catholic rulers until mid-September 1598. On 28 September, all the teachers, including Kepler, were abruptly ordered to leave town before sunset. Although, unlike his colleagues, he was allowed to return, conditions remained tense; and Kepler tried vainly to secure a position at Tübingen. In August 1599 he learned that [Tycho Brahe](#) had gone to the court of Rudolph II in Bohemia, so he set out in January 1600 for an exploratory visit to the great Danish astronomer, arriving at Tycho's Benatky Castle observatory outside Prague early in February.

Although Tycho welcomed him "not so much as a guest but as a highly desirable participant in our observations of the heavens," he promptly treated the sensitive Kepler as a beginner. Kepler at first had little opportunity to participate except at meals, "where one day Tycho mentioned the apogee of one planet, the next day the nodes of another."⁹ Conscious of his own genius, Kepler expected to be regarded as an independent investigator; plagued by the financial worries as well as the uncertainties of his position, either in Graz or in Prague, he brought the matter to a heated crisis early in April. Happily, a reconciliation followed, and Kepler worked another month at Benatky before going to Prague and thence back to Graz.

Kepler had quickly perceived the quality of Brahe's treasure of observations, but he realized that Tycho lacked an architect for the erection of a new astronomical structure. By Divine Providence, as he was later to view it, Kepler was assigned to the theory of Mars; and in his three months at Benatky he established two fundamental points: first, the orbital place of Mars must be referred to the true sun, and not to the center of the earth's orbit, as previous astronomers had assumed; and second, the traditional mechanism for the earth-sun relation had to be modified to include an equant. The equant, a seat of uniform angular motion within a circular orbit, satisfied Kepler's physical intuition that a planet must move proportionally more quickly when it is closer to the sun (see Fig. 3). Although the other planetary mechanisms

had traditionally employed the equant, the earth-sun system did not. Hence, it was of paramount importance to Kepler's physics to prove that the earth's motion resembled those of the other planets, and this he accomplished by an ingenious triangulation from the earth's orbit to Mars.

Kepler continued his astronomical studies after his return to Graz, working on geometrical theorems relating to the Mars problem and building a projection device for observing the solar eclipse of 10 July 1600. Shortly after, his work was interrupted by a commission of the Counter-reformation; Kepler was examined on 2 August and was among the sixty-one men banished from Graz for refusing to change their faith. Although he was uncertain which way to turn, the deadline for leaving allowed little time for negotiations; consequently, Kepler left Graz with his family on 30 September. At Linz a hoped-for letter from Maestlin had not arrived. Depressed and in poor health, Kepler arrived in Prague on 19 October. Tycho gladly took Kepler back, especially because his chief assistant, Longomontanus, had just resigned.

Kepler resumed his work on Mars, notably his attempt to fit the observations with a circular orbit and equant. He departed from the traditional procedure by allowing the equant to fall at an arbitrary point along the line joining the sun and the center of the orbit (see Fig. 3); in principle the minimum error in heliocentric longitude from this model is only about one minute of arc. By the spring of 1601 he had achieved a far more accurate solution for the longitudes than had any of his predecessors, but the latitudes were not satisfactory.

Meanwhile, Tycho had assigned to Kepler the unhappy task of composing a defense against Nicolaus Raymarus Ursus, whom Tycho accused of plagiarism. Kepler's contacts with Ursus dated back to 1595, when, as a still-unknown youth, he had written Ursus a letter praising him as the leading mathematician of the age. In 1597 Ursus incorporated the letter into a venomous attack on Brahe. The embarrassed Kepler blamed the extravagance of his letter on his own immaturity, but the incident continued to rankle Tycho, who must have found grim satisfaction in requiring Kepler to write the rebuttal. Kepler, however, took the opportunity to analyze the nature of scientific hypotheses and to sharpen his own arguments on the truth of the Copernican premises. "If in their geometrical conclusions two hypotheses coincide, nevertheless in physics each will have its own peculiar additional consequence."¹⁰ Thus the stage was set for the critical distinction between the "Vicarious" and the "physical" hypotheses in his Mars researches the following spring.

Kepler returned to Graz in April 1601, on a futile trip to look after his wife's inheritance. The visit dragged on, his wife wrote from Prague of her financial worries, and Kepler responded indignantly to Brahe. Kepler returned to Prague at the end of August, and the differences with Brahe were patched up. Nevertheless, Kepler continued to chafe under the secretive jealousy with which Tycho guarded his observations. Then, suddenly, the Danish astronomer fell ill; and on 24 October 1601 he died. On his deathbed Tycho urged Kepler to complete the proposed *Rudolphine Tables* of planetary motion, adding his hope that they would be framed according to the Tyconic hypothesis. Within two days Kepler received the appointment to Tycho's post of imperial mathematician, although five months passed before he received his first salary.

Kepler's encounter with Tycho had been a fateful one—"God let me be bound with Tycho through an unalterable fate and did not let me be separated from him by the most oppressive hardships,"¹¹ he wrote—yet he had worked with the Danish master altogether less than ten months. Kepler always spoke of Tycho with high esteem; but clearly Tycho's unexpected death freed Kepler to work out the planetary theory without the continual strain that had characterized their relationship.

As the first step toward the construction of the *Rudolphine Tables*, Kepler continued to perfect the quasi-traditional circular orbit with its equant, which yielded heliocentric longitudes accurate to 2'; "If you are wearied by this tedious procedure," he later implored his readers, "take pity on me who carried out at least seventy trials."¹² From the predicted latitudes, however, he realized that his model gave erroneous distances; unlike previous astronomers, who were satisfied with separate mathematical mechanisms for the longitudes and latitudes, Kepler sought a unified, physically acceptable model. Thus, by the spring of 1602 he began to distinguish between the "vicarious hypothesis" that he had achieved and the desired "physical hypothesis." To obtain the correct distances that a physical model demanded, he was obliged to reposition his circular orbit with its center midway between the sun and the equant (unlike Fig. 3). With this bisected eccentricity, the error in heliocentric longitude rose to 6' or 8' in the octants. "Divine Providence granted us such a diligent observer in Tycho Brahe," wrote Kepler, "that his observations convicted this Ptolemaic calculation of an error of 8'; it is only right that we should accept God's gift with a grateful mind. . . . Because these 8' could not be ignored, they along have led to a total reformation of astronomy."¹³

Kepler now revised his earlier speculations on the planetary driving force emanating from the sun. Jean Taisner's book on the magnet (1562) and, later, [William Gilbert](#)'s convinced him that the force might be magnetic. Kepler envisioned a rotating sun with a rotating field of magnetic emanations that continuously drove the planets in their orbits. He supposed that such a force would act only in the planes of the orbits, and consequently (unlike light) would diminish inversely with distance. Kepler's new model with bisected eccentricity, especially of the earth's orbit, enabled him to formulate what we can call his distance law: that the orbital velocity of a planet is inversely proportional to its distance from the sun. Although this holds strictly only at aphelion and perihelion, Kepler promptly generalized the relation to the entire orbit. Controlling the angular motion by his distance law immediately raised a difficult quadrature problem that could be solved only by tedious numerical summations. Here he had the fortunate inspiration to replace the sums of the radius vectors (that is, the lines from the sun to the planet) required by the distance law with the area within the orbit. Thus the radius vector swept out equal areas in equal times. Kepler recognized that this was mathematically objectionable, but like a miracle the predicted longitudes matched the observations. Today it is called his second law, but nowhere in his great book on Mars is the area rule clearly stated. Kepler properly understood its fundamental nature only later, when he based the calculations of the *Rudolphine Tables* on it; and both the area law and a revised distance law are correctly stated in book V of his *Epitome astronomiae Copernicanae* (1621).

Whereas the area law worked well for the earth's orbit, when it was applied to Mars the eight-minute discrepancy again appeared. Kepler recognized at once that a noncircular orbit could provide a solution, although the area law itself was still suspect. A triangulation to three points on the Martian orbit confirmed that Mars's path bowed in from a circle, but the exact amount was difficult to establish. Kepler now resumed an exploration of the effects of a small epicycle, which he had started in 1600. He knew from the traditional model for Mercury that its epicycle produced an oval or, more properly, an ovoid curve. His attempts to find a quadrature for the ovoid and to confirm the area law led, in Kepler's own words, to a veritable labyrinth of calculation. In fact, the difference between the longitudes generated from the distance law and the area law reaches 4', precariously close to the eight-minute discrepancy that had driven him to a renewed assault on the problem. Writing to David Fabricius in July 1603, Kepler noted, "I lack only a knowledge of the geometric generation of the oval or face-shaped curve. . . . If the figure were a perfect ellipse, then Archimedes and Apollonius would be enough."¹⁴ As shown with exaggerated

eccentricity in Figure 4, the ovoid is quite similar to an ellipse; but since the approximating ellipse has an eccentricity of e (where e is the eccentricity of the true ellipse), it has no physical connection with the sun.

Kepler spent most of his effort from September 1602 to the end of 1603 on his *Astronomiae pars optica* (see below), but in 1604 he began in earnest to prepare his *Astronomianova or Commentarius de stella martis*. In December he wrote to Fabricius: "I am now completely immersed in the *Commentarius*, so that I can hardly write fast enough." By early 1605 he had completed fifty-one chapters without yet discovering the ellipse. By now, however, Kepler must have realized that his problems lay not with an inadequate quadrature but in his defective knowledge of the size of the crescent-shaped lunula by which the path of Mars departed from a circle.

His renewed assault included a revised triangulation to the Martian orbit, carried out by coupling observed geocentric position angles with the heliocentric longitudes predicted by his accurate but physically unacceptable vicarious hypothesis. The results showed that the true orbit lay midway between the oval and circle (see Fig. 4), and thus his elaborately reasoned physical causes for the ovoid itself "went up in smoke."

These physical causes were an extension of the magnetic emanation that drove the planets around the sun: The sun's presumed unipolar magnetism could act on a planet's magnetic axis with a fixed direction in space, and could alternately attract and repel the planet from the sun. Thus the same mechanism might, he hoped, account for both the varying speed of a planet in its orbit and its varying distance from the sun. His goal, as he wrote J. G. Herwart von Hohenburg in February 1605, was "to show that the celestial machine is not so much a divine organism but rather a clockwork . . . inasmuch as all the variety of motions are carried out by means of a single very simple magnetic force of the body, just as in a clock all the motions arise from a very simple weight."¹⁵

Kepler had invested so much speculative energy justifying the "librations" produced by the epicycle (even though he was simultaneously repelled by the epicycle's lack of physical properties) that he refused to abandon his idea. Thus, he now proceeded to another epicyclic construction, the *via buccosa* or "puffy-cheeked" (as distinguished from the oval, "face-shaped") curve. Although this curve matches within the accuracy of Tycho's observations, Kepler made a conceptual error in his calculation and therefore found a disagreement; thus he felt justified in rejecting it. By this time he realized that an ellipse would satisfy the observations but he could not at first connect an ellipse with the magnetic hypothesis. In chapter 58 he writes:

I was almost driven to madness in considering and calculating this matter. I could not find out why the planet would rather go on an elliptical orbit. Oh, ridiculous me! As if the libration on the diameter could not also be the way to the ellipse. So this notion brought me up short, that the ellipse exists because of the libration. With reasoning derived from physical principles agreeing with experience, there is no figure left for the orbit of the planet except a perfect ellipse.

Kepler had thus arrived at what we now call his first law, that the planetary orbits are ellipses with the sun at one focus. With justifiable pride he could call his book "The New Astronomy." Its subtitle emphasizes its repeated theme: "Based on Causes, or Celestial Physics."

Unfortunately, publication of the work did not proceed promptly, partly from the lack of imperial financial support but mostly because of interference from the "Tychonians." Emperor Rudolph II had offered the heirs 20,000 talers for Tycho's observations but had actually paid only a few thousand. Consequently the heirs, particularly the nobleman Franz Gansneb Tegnagel (who had married Tycho's daughter), held a vested interest in the data. Tegnagel, although unqualified, promised his own publication and, after failing to produce, threatened to suppress Kepler's commentary. Then a compromise was reached: Tegnagel was allowed a preface to warn the readers not to "become confused by the liberties that Kepler takes in deviating from Brahe in some of his expositions, particularly those of a physical nature." The printing finally began at Heidelberg in 1608, and the *Astronomianova* was published in the summer of 1609. Although the distribution of the large and magnificent folio was a privilege held by the emperor, Kepler eventually sold the edition to the printer in an attempt to recover part of his back salary.

The Nova of 1604. Of the various astrological matters on which Rudolph II sought Kepler's opinion, the great conjunction of Jupiter and Saturn in 1603 was particularly remarkable. Such conjunctions occur every twenty years; only comets were considered more ominous. As shown in Figure 1, the conjunctions fall in a regular pattern, so that a series of ten occurs within a particular zodiacal "trigon," one of the four sets designated by astrologers according to the Aristotelian elements; in an 800-year cycle the conjunctions pass through all four trigons. The conjunction at the end of 1603 marked the beginning of the 200-year series within the fiery trigon. Excitement reached a peak in October 1604, when a brilliant new star unexpectedly appeared within a few degrees of Jupiter, Saturn, and Mars.

Kepler at once published in German an eight-page tract on the new star, describing its appearance and comparing it to Tycho's nova of 1572. Then he allowed himself a frivolous prediction: the nova portended good business for booksellers, because every theologian, philosopher, physician, mathematician, and scholar would have his own ideas and would want to publish them.

Kepler's extensive collection of observations and opinions appeared in a longer work, *De stella nova*, in 1606. A subtitle announced it as "a book full of astronomical, physical, metaphysical, meteorological and astrological discussions, glorious and unusual." That it was Early chapters described the nova's appearance, astrological significance and possible origin. He rejected

the Possibility possible origin. He rejected the possibility of a chance configuration of atoms, and in a charming passage presented

. . . not my own opinion, but my wife's. Yesterday, when weary with writing, I was called to supper, and a salad I had asked for was set before me. "It seems then," I said, "if pewter dishes, leaves of lettuce, grains of salt, drops of water, vinegar, oil and slices of eggs had been flying about in the air from all eternity, it might at last happen by chance that there would come a salad." "Yes," responded my lovely, "but not so nice as this one of mine."¹⁶

In chapter 21 Kepler argued that stars are not suns, but his well-reasoned case rested on an erroneously large angular diameter of the stars. Finally, he meditated on the astrological interpretations of the nova: conversion of the Indians in America, a universal migration to the new world, the downfall of Islam, or even the return of Christ. His speculations broke off abruptly; as a "good and peaceful German," as he called himself, he had avoided controversy; and he urged his readers, in the presence of a "astronomers have preferred its faithful descriptions" celestial sign, to examine their sins and repent.

De stella nova is a monument of its time but the least significant of Kepler's major works. It broke no new astronomical ground, although twentieth-century astronomers have preferred its faithful descriptions over numerous other accounts when searching the literature to help distinguish supernovae from ordinary novae.

In terms of Kepler's own scholarly effort, the appendix was the most important part. In its dedicatory epistle he spoke of entering a "chronological forest," and the printer seized upon *Sylva chronologica* as the running title. In 1605 Kepler had come upon a tract by Lawrence Suslyga that argued for 5 B.C. as the date of Christ's birth. Nothing that an initial conjunction in the fiery trigon, comparable with the one in 1603, presumably had occurred in 5 B.C., Kepler drew an analogy between the nova of 1604 and the star of the Magi; following Suslyga's arguments in part, he settled upon 5 B.C. as the year of Christ's birth. (A similar adjustment is commonly accepted today for chronological reasons.) Afterward, Kepler elaborated his arguments in several works, including his definitive account, *De vero anno*. . . (1614).

Optical Researches. Kepler's interest in optics arose as a direct result of his observations of the partial solar eclipse of 10 July 1600. Following instructions from Tycho Brahe, he constructed a pinhole camera; his measurements, made in the Graz marketplace, closely duplicated Brahe's and seemed to show that the moon's apparent diameter was considerably less than the sun's. Kepler soon realized that the phenomenon resulted from the finite aperture of the instrument (see Fig. 5); his analysis, assisted by actual threads, led to a clearly defined concept of the light ray, the foundation of modern geometrical optics.

Kepler's subsequent work applied the idea of the light ray to the optics of the eye, showing for the first time that the image is formed on the retina. He introduced the expression "pencil of light," with the connotation that the light rays draw the image upon the retina; he was unperturbed by the fact that the image is upside down.

Kepler constructed an expression for the traditional "angle of refraction," that is, the difference between the angles of the incident and refracted rays, as

$$i - r = n \cdot i \cdot \sec r,$$

where n is the index of refraction. He arrived at this result at least partly by theoretical considerations of the resistance offered by the denser medium. His formulation matched the somewhat erroneous data given by Witelo just as well as the correct sine law of refraction did. Descartes, the discoverer of the sine law in its modern form, acknowledged to Mersenne that "Kepler was my principal teacher in optics, and I think that he knew more about this subject than all those who preceded him."¹⁷

Kepler intended at first to publish his optical analyses merely as *Ad Vitellionem paralipomena*, but by 1602 this "Appendix to Witelo" had taken second place to the broader program of *Astronomiae pars optica*. The book was published in 1604 with both titles, but Kepler regularly referred to his work by the latter. The six astronomical chapters include not only a discussion of parallax, astronomical refraction, and his eclipse instruments but also the annual variation in the apparent size of the sun. Since the changing size of the solar image is inversely proportional to the sun's distance, this key problem was closely related to his planetary theory; unfortunately, his observational results were not decisive.

The immediate impact of Kepler's optical work was not great; but ultimately it changed the course of optics, especially after his *Dioptrice* (1611), which applied these principles to the telescope. "Optical tubes" had been discussed in [Giambattista della Porta's *Magia naturalis*](#) (1589); but Kepler confessed that "I disparaged them most vigorously, and no wonder, for he obviously mixes up the incredible with the probable."¹⁸ Thus Kepler, who himself used spectacles, discussed lenses only in passing in his *Astronomiae pars optica*. Nevertheless, he had set forth the essential background by which the formation of images with lenses could be explained, and so he was able to complete his *Dioptrice* within six months after he had received Galileo's *Sidereus nuncius* (1610). With great thoroughness Kepler described the optics of lenses, including a new kind of astronomical telescope with two convex lenses. The preface declares, "I offer you, friendly reader, a mathematical book, that is, a book that is not so easy to understand," but his severely mathematical approach only serves to place the *Dioptrice* all the more firmly in the mainstream of seventeenth-century science.

Minor Works. On 8 April 1610 Kepler received a copy of Galileo's *Sidereus nuncius*, and a few days later the Tuscan ambassador in Prague transmitted Galileo's request for an opinion about the startling new telescopic discoveries. What a contrast with 1597, when Kepler, an unknown high-school teacher, had sought in vain Galileo's reaction to his own book! Kepler was now the distinguished imperial mathematician, whose opinion mattered; he responded generously and quickly with a long letter of approval.

He promptly published his letter as *dissertatio cum nuncio sidereo*; in accepting the new observations with enthusiasm, he also reminded his readers of the earlier history of the telescope, his own work on the regular solids and on possible inhabitants of the moon, and his arguments against an infinite universe. A few months later, in the second of the only three known letters that Galileo wrote directly to Kepler, the Italian astronomer stated, "I thank you because you were the first one, and practically the only one, to have complete faith in my assertions."¹⁹

Not until August 1610 was Kepler's great desire to use a telescope satisfied, when Elector Ernest of Cologne lent him one. From 30 August to 9 September, Kepler observed Jupiter; he published the results in *Narratio de Jovis satellitibus* (1611), a booklet that was quickly reprinted in Florence. It provided a strong witness to the authenticity of the new discoveries.

Three other short works from Kepler's Prague period deserve mention. In *Phaenomenon singulare* (1609) he reported on a presumed transit of Mercury that he had observed on 29 May 1607. Unfortunately, Kepler had caught between clouds only two glimpses of a "little daub" that appeared on the solar image projected through a crack in the roof. After Galileo's discovery of sunspots, Maestlin pointed out the error and Kepler ultimately printed a retraction in his *Ephemerides* for 1617, noting that unwittingly he had been the first of his century to observe a sunspot.

In *Tertius interveniens* (1610) Kepler played the role of the "third man in the middle" both against those who uncritically accepted grotesque astrological predictions and against those critics who would "throw out the baby with the bath." Writing in the vernacular German interspersed with numerous scraps of Latin, Kepler argued: "No one should consider unbelievable that there should come out of astrological foolishness and godlessness also cleverness and holiness . . . out of evil-smelling dung a golden corn scraped for by an industrious hen."²⁰ As part of the dung he counted most astrological rules, including the distinctions of the zodiacal signs and the meanings of the twelve houses. Kepler insisted, however, on the harmonic significance of the configurations of the planets among themselves and with ecliptic points such as the ascendant. The stars do not compel, he said, but they impress upon the soul a special character.

In his *Strena* (1611), "A [New Year's](#) Gift, or On the Six-Cornered Snowflake," Kepler ponders the problem of why snowflakes are hexagonal. Composed as a present for his friend at court, Counselor J. M. Wackher, it is not only a charming letter, light-hearted and full of puns, but also a perceptive, pioneering study of the regular arrangements and the close packing that are fundamental in crystallography.

Linz. In the spring of 1609 Kepler journeyed to the Frankfurt Book Fair; to Heidelberg, where the *Astronomianova* was being printed; and also, for the first time in thirteen years, to Tübingen. While in Swabia he attempted to pave the way for a permanent return to his homeland by sending a petition to the duke of Württemberg, reminding him how quickly troubles might arise, leaving Kepler unemployed. Nevertheless, under Rudolph's patronage his position in Prague seemed secure despite the increasing religious turmoil. But in 1611 Kepler's world suddenly collapsed. His wife became seriously ill; and his three children were stricken with smallpox. His favorite son died. Prague became a scene of bloodshed; and in May, Rudolph was forced to abdicate.

Kepler turned once more to the duke of Württemberg, but his cherished hopes of returning to Tübingen as a professor were finally dashed when the Württemberg theologians objected to his friendliness with Calvinists and to his reservations about the Formula of Concord. Earlier, Kepler had been invited to Linz as provincial mathematician, a post created specially for him; his decision to go there was motivated in part by a desire to find a town more congenial to his wife. Before the move took place, however, Barbara Kepler was infected by the typhus carried into Prague by the troops; and on 3 July 1611 she died. Meanwhile, the deposed Rudolph demanded Kepler's presence, and not until the monarch's death in January 1612 was the lonely astronomer free to leave Prague. Simultaneously his appointment as imperial mathematician was renewed.

Although Kepler's most creative period lay behind him, his fourteen-year sojourn in Linz eventually saw the production of his *Harmonice mundi* and *Epitome astronomiae Copernicanae* and the preparation of the *Tabulae Rudolphinae*. His stay in Linz started badly, however, for the local Lutheran pastor, who knew the opinion of the Württemberg theologians, excluded him from communion when he refused to sign the Formula of Concord. Kepler did not accept the exclusion willingly and produced repeated appeals to the Württemberg consistory and to his Tübingen teacher, Matthias Hafenreffer, but always in vain. While his coreligionists considered him a renegade, the Catholics tried to win him to their side. When the Counter-reformation swept into Linz in 1625, an exception was made so that he was not banished; but his library was temporarily sealed and his children were forced to attend the Catholic services. Thus Kepler, a peaceful and deeply religious man, suffered greatly for his conscience' sake throughout his life and especially in Linz.

One bright spot in his Linz career was his second marriage, to Susanna Reuttinger, a twenty-four-year-old orphan, on 30 October 1613. In an extraordinary letter to an unidentified nobleman, Kepler details his slate of eleven candidates for marriage and explains how God had led him back to number five who had evidently been considered beneath him by his family and

friends. The marriage was successful, far happier than the first; but of their seven children, five died in infancy or childhood. Likewise, only two of the five children of his first marriage survived to adulthood.

That Kepler, engulfed in a sea of personal troubles, published no astronomical works from 1612 through 1616 is not surprising. Yet he did produce the *Stereometria doliorum vinariorum* (1615), which is generally regarded as one of the significant works in the prehistory of the calculus. Desiring to outfit his new household with the produce of a particularly good wine harvest, Kepler installed some casks in his house. When he discovered that the wine merchant measured only the diagonal length of the barrels, ignoring their shape, Kepler set about computing their actual volumes. Abandoning the classical Archimedean procedures, he adopted a less rigorous but productive scheme in which he considered that the figures were composed of an infinite number of thin circular laminae or other cross sections. Captivated by the task, he extended it to other shapes, including the torus.

In 1615 Kepler brought the first printer to Linz, and thus the *Stereometria* was the first work printed there. He had hoped to profit from his book; and when sales lagged, he edited a considerably rearranged popular German version, the *Messekunst Archimedis* (1616). Incidentally, his work proved that the simple gauging rod was valid for Austrian wine casks.

Harmonice Mundi. The Linz authorities were not entirely pleased that Kepler had taken three-quarters of a year to produce the *Stereometria*, for his appointment had charged him first of all to complete the astronomical tables long since proposed by Tycho. They urged him to get on with the important *Tabulae Rudolphinae*. But to a correspondent, Kepler responded, “Don’t sentence me completely to the treadmill of mathematical calculations—leave me time for philosophical speculations, my sole delight.”²¹

In 1599 Kepler had drafted a plan for a work on the harmony of the universe; but since he had left Graz, his cosmological studies had lain comparatively dormant. Meanwhile, in 1607 he had finally obtained a Greek manuscript of Ptolemy’s *Harmony*, and he was further stimulated by the Neoplatonic views of Proclus’ commentary on Euclid. Alongside his studies of mathematical and musical harmony, he was formulating an astrological world view consonant with the laws of harmony. Thus, after he had completed his *Ephemerides* for 1617 in November 1616, he began to work intermittently on his *Harmonice mundi* but devoted most of his time to his tables and to the first part of his *Epitome*.

In the fall of 1617 Kepler was forced to journey to Württemberg to arrange the defense for his mother’s witchcraft trial. In September the first daughter of his second marriage had died; and in February 1618, several weeks after his return to Linz, his second infant daughter died. Distraught and oppressed, he wrote, “I set the tables aside since they required peace, and turned my mind to refining the *Harmonice*”.²² A major work of 255 pages, the five parts of the *Harmonice mundi* were swiftly completed by 27 May 1618, although the final section was further revised while the type was being set

Max Caspar, in his biography *Kepler*, gives an extended and perceptive summary of the *Harmonice*, concluding:

Certainly for Kepler this book was his mind’s favorite child. Those were the thoughts to which he clung during the trials of his life and which brought light to the darkness that surrounded him . . . With the accuracy of the researcher, who arranges and calculates observations, is united the power of shaping of an artist, who knows about the image, and the ardor of the seeker for God, who struggles with the angel. So his *Harmonice* appears as a great cosmic vision, woven out of science, poetry, philosophy, theology, mysticism . . .²³

Kepler developed his theory of harmony in four areas: geometry, music, astrology, and astronomy. In the short book I he examined the geometry of polygons with an eye to their constructability. In the second book he investigated both polygons and polyhedrons, especially for their properties of filling a plane or space. He was here the first to introduce the great and small stellated dodecahedrons. (In 1810 Louis Poincaré rediscovered these, along with the two other examples of this class; the four polyhedrons are now known as the Kepler-Poincaré solids.)

Kepler’s notion that the archetypal principles of the universe were based on geometry rather than on number found confirmation in book III, on musical harmony. He could not see any sufficient reason why God should have chosen the numbers 1, 2, 3, 4, 5, 6 for generating musical consonances and have excluded the numbers 7, 11, 13, and so on. He knew, of course, that the regular polygons produced only five regular polyhedrons and he sought some other procedure with polygons to yield the seven ratios that had only within his lifetime become commonly accepted as the basis for the “just” scale: 1/2, 2/3, 3/4, 4/5, 5/6, 3/5, and 5/8. By appropriately dividing those polygons that could be easily constructed with a rule and compass, he convinced himself of a rationale for these ratios and no others. Had he stuck to the ancient Greek system of intonation, with only the consonances 1/2, 2/3, and 3/4, his geometrical rationalization would have been much simpler; but apparently he had adopted the just intonation by actually listening to the harmonies. (One authority on modern music that Kepler cites is Galileo’s father, Vincenzo, whose *dialogo della antica e moderna* [1581] he read during his 1617 journey to Württemberg.)

Kepler’s astrological views, already expounded in the *De stella nova* and *Tertius interveniens*, found their fully organized expression in book IV of the *Harmonice mundi*. In his theory of aspects, the geometrically formed soul created the zodiac as a projection of itself. Thus, the heavenly bodies traveling on the zodiac produced an excitement within the soul whenever they formed angles corresponding to those of the regular polygons. The form of the planetary configurations at one’s birth remained

impressed on his soul for the whole of his life. As the spur was to the horse, or the trumpet to the soldier, so was the so-called influence of the heavens to the soul. For the benefit of other astrologers, Kepler gave his own nativity, adding:

My stars were not Mercury rising in the seventh angle in quadrature with Mars, but Copernicus and Tycho Brahe, without whose observation books everything that I have brought into the clearest light would have remained in darkness; my rulers were not Saturn predominating over Mercury, but the emperors Rudolph and Matthias; not a planetary house, Capricorn with Saturn, but Upper Austria, the house of the emperor.²⁴

The earth, too, participated in the cosmic harmony; its soul held a bond of sympathy with the entire firmament. Although in the introduction to the *Astronomianova* Kepler had already explained the tides by the moon's attraction, as he noted here, he nevertheless now proceeded to interpret them as the breathing of the earth like an enormous living animal. Swept on by his fantasy, Kepler found animistic analogies everywhere. Yet in his *Epitome astronomiae Copernicanae*, written at almost the same time, he stated: "No soul oversees this revolution (of the planet. . .), but there is the one and only solar body, situated in the middle of the entire universe, to which this motion of the primary planets about the sun can be ascribed."²⁵

In the *Mysterium cosmographicum* the young Kepler had been satisfied with the rather approximate planetary spacings predicted by his nested polyhedrons and spheres; now, imbued with a new respect for data, he could no longer dismiss its 5 percent error. In the astronomical book V of the *Harmonice mundi*, he came to grips with this central problem: By what secondary principles did God adjust the original archetypal model based on the regular solids? Indeed, he now found a supposed harmonic reason not only for the detailed planetary distances but also for their orbital eccentricities. The ratios of the extremes of the velocities of the planets corresponded to the harmonies of the just intonation. Of course, one planet would not necessarily be at its perihelion when another was at aphelion. Hence, the silent harmonies did not sound simultaneously, but only from time to time as the planets wheeled in their generally dissonant courses around the sun. Swept on by the grandeur of his vision, he exclaimed:

It should no longer seem strange that man, the ape of his Creator, has finally discovered how to sing polyphonically, an art unknown to the ancients. With this symphony of voices man can play through the eternity of time in less than an hour and can taste in small measure the delight of God the Supreme Artist by calling forth that very sweet pleasure of the music that imitates God.²⁶

In the course of this investigation, Kepler hit upon the relation now called his third or harmonic law: The ratio that exists between the periodic times of any two planets is precisely the ratio of the $3/2$ power of the mean distances. Neither here nor in the few later references to it does he bother to show how accurate the relation really is. Yet the law gave him great pleasure, for it so neatly linked the planetary distances with their velocities or periods or periods, thus fortifying the a priori premises of the *Mysterium* and the *Harmonice*. So ecstatic was Kepler that he immediately added these rhapsodic lines to the introduction to book V:

Now, since the dawn eight months ago, since the broad daylight three months ago, and since a few days ago, when the full sun illuminated my wonderful speculations, nothing holds me back. I yield freely to the sacred frenzy; I dare frankly to confess that I have stolen the golden vessels of the Egyptians to build a tabernacle for my God far from the bounds of Egypt. If you pardon me, I shall rejoice; if you reproach me, I shall endure. The die is cast, and I am writing the book — to be read either now or by posterity, it matters not. It can wait a century for a reader, as God himself has waited six thousand years for a witness.²⁷

At the instigation of a third party, Kepler appended a comparison of the "colossal difference" between his theory and that of [Robert Fludd](#), the Oxford physician and Rosicrucian. The ensuing controversy at least illuminates the intellectual climate of the early 1600's, when the new, quantitative mathematical approach to nature collided with the qualitative, symbolical, alchemical tradition. Fludd counterattacked in an arrogant, polemical pamphlet, to which Kepler replied in his *Pro suo opere Harmonice mundi apologia* (1622). The *Apologia* was appended to a reissue of his *Mysterium cosmographicum*. Although republished in a larger format, the 1596 text of *Mysterium* was unchanged. Numerous new footnotes called attention to the subsequent work, especially in the *Harmonice mundi*.

On Comets. In *De Cometis libellitres* (1619) Kepler discussed in detail the bright comets of 1607 and 1618. Reflecting on the ephemeral nature of comets, he proposed a strictly rectilinear trajectory, which of course appeared more complex because of the earth's motion. Some decades later [Edmond Halley](#) made extensive use of the observations recorded in this book when he showed the seventy-six-year periodicity of the comet of 1607. The brief second section of Kepler's trilogy concerned the "physiology of comets": they fill the ether as fish fill the sea but are dissipated by the sun's light, forming the tail that points away from the sun. The final section treated the significations of the comets. Although he asserted that the common astrological beliefs rested on superstition, Kepler was still convinced that comets announced evil and misfortune. In those politically uncertain times, however, he wisely refrained from any specific prognostications.

A few years later Kepler published the *Hyperaspistes* (1625), a polemical defense of Tycho's comet theories against the Aristotelian views expressed by Scipione Chiaramonti in his *Antitycho*. As Delambre remarked, one regrets that Kepler took such pains with a point-by-point refutation, because the book is difficult to read in its entirety. More interesting is the appendix, which takes Galileo to task for some of the same erroneous views on comets. Kepler brings to Galileo's attention the fact that the observed phases of Venus can be as easily explained by the Tychonic as by the [Copernican system](#).

The Epitome. Despite its title, Kepler's *Epitome astronomiae Copernicanae* was more an introduction to Keplerian than to Copernican astronomy. Cast in a catechetical form of questions and answers typical of sixteenth-century astronomy textbooks, it treated all of heliocentric astronomy in a systematic way, including the three relations now called Kepler's laws. Its seven books were issued in three installments. Taken together, they constitute a squat, unprepossessing octavo volume whose physical appearance scarcely marks it as Kepler's longest and most influential work. J. L. Russell has maintained that from 1630 to 1650 the *Epitome* was the most widely read treatise on theoretical astronomy in Europe. ²⁸

The composition of the *Epitome* was closely intertwined with the personal vicissitudes of its author's life. Although he had been pressed for a more popular book on Copernican astronomy when his very technical *Astronomianova* appeared, not until the spring of 1615 were the first three books ready for the printer. This part finally appeared in 1617, having been delayed a year because, even though he had previously signed a contract with an Augsburg publisher, Kepler wanted the work done by his new Linz printer. By that time his seventy-year-old mother had been charged with witchcraft, and the astronomer felt obliged to go to Württemberg to aid in her legal defense. Afterward, the writing of the *Harmonice mundi* interrupted progress on the *Epitome*, so that the second installment, book IV, did not appear until 1620. The printing was barely completed when Kepler again journeyed to Württemberg, this time for the actual witchcraft trial. During pauses in the proceedings, he consulted with Maestlin at Tübingen about the lunar theory and arranged the printing of the last three books in Frankfurt. The publisher completed his work in the autumn of 1621, just as Kepler's mother won acquittal after enduring the threat of torture.

The first three books of this compendium deal mainly with spherical astronomy. Occasionally Kepler went beyond the conventional subject matter, considering, for example, the spatial distribution of stars and atmospheric refraction. Of special interest are the arguments for the motions of the earth; in describing the relativity of motion, he went considerably further than Copernicus and correctly formulated the principles later given more detailed treatment in and as a result of the anti-Copernican furor stirred up by Galileo's *Dialogo* (1632). Because of these arguments, up by Galileo's polemical writings, the *Epitome* was placed on the *Index Librorum Prohibitorum* in 1619. In spite of assurances that his works would be read all the more attentively in Italy, Kepler was alarmed; fearing that the circulation of his *Harmonice mundi* might also be restricted, he urged Italian book dealers to sell his works only to the highest clergy and the most important philosophers.

The most remarkable section of the *Epitome* was book IV, on theoretical astronomy, subtitled, "Celestial Physics, That Is, Every Size, Motion and Proportion in the Heavens Is Explained by a Cause Either Natural or Archetypal" In conception this installment came after books V-VI, and to a great extent it epitomized both the *Harmonice mundi* and the new lunar theory that Kepler completed in April 1620.

Book IV opened with one of his favorite analogies, one that had already appeared in the *Mysterium cosmographicum* and that stressed the theological basis of his Copernicanism: The three regions of the universe were archetypal symbols of [the Trinity](#) — the center, a symbol of the Father; the outermost sphere, of the Son; and the intervening space, of the [Holy Spirit](#). Immediately thereafter Kepler plunged into a consideration of final causes, seeking reasons for the apparent size of the sun, the length of the day, and the relative sizes and the densities of the planets. From first principles he attempted to deduce the distance of the sun by assuming that the earth's volume is to the sun's as the radius of the earth is to its distance from the sun. Nevertheless, his assumption was tempered by a perceptive examination of the observations. In their turn the nested polyhedrons, the harmonies, the magnetic forces, the elliptical orbits, and the law of areas also found their place within Kepler's astonishing organization.

The harmonic law, which Kepler had discovered in 1619 and announced virtually without comment in the *Harmonice mundi*, received an extensive theoretical justification in the *Epitome*, book IV, part 2, section 2. His explanation of the $P=a^{3/2}$ law, in modern form, was based on the relation

where the longer the path length L , the longer the period; the greater the strength S of the magnetic emanation, the shorter the period (this magnetic "species," emitted from the sun, provided the push to the planet); the more matter M in the planet, the more inertia and the longer the period; the greater the volume V of the planet, the more magnetic emanation could be absorbed and the shorter the period. According to Kepler's distance rule, the driving force S was inversely proportional to the distance a , and hence L/S was proportional to a^2 ; thus the density M/V had to be proportional to $1/a^{1/2}$ in order to achieve the 3/2 power law. Consequently, he assumed that the density (as well as both M and V) of each planet depended monotonically on its distance from the sun, a requirement quite appropriate to his ideas of harmony. To a limited extent he could defend his choice of V from telescopic observations of planetary diameters, but generally he was obliged to fall back on vague archetypal principles.

The lunar theory, which closed book IV of the *Epitome*, had long been a preoccupation of its author. In Tycho's original division of labor, Kepler had been assigned the orbit of Mars and Longomontanus that of the moon; but not long after Tycho's death Kepler applied his own ideas of physical causes to the lunar motion. To Longomontanus' angry remonstrance Kepler replied that it was not the same with astronomers as with smiths, where one made swords and another wagons.²⁹ He believed that the moon would undergo magnetic propulsion from the sun as well as from the earth, but the complicated interrelations gave much difficulty. In 1616 Maestlin wrote to him:

Concerning the motion of the moon, you write that you have traced all the inequalities to physical causes; I do not quite understand this. I think rather that one should leave physical causes out of account, and should explain astronomical matters only according to astronomical method with the aid of astronomical, not physical, causes and hypotheses. That is, the calculation demands astronomical bases in the field of geometry and arithmetic. . . ³⁰

In other words, the circles, epicycles, and equants that Kepler had ultimately abandoned in his *Astronomianova*.

Kepler persisted in seeking the physical causes for the moon's motion and by 1620 had achieved the basis for his lunar tables. The fundamental form of his lunar orbit was elliptical, but the positions were further modified by the evection and by Tycho's so-called variation. Kepler's lunar theory, as given in book IV of the *Epitome*, failed to offer much foundation for further advances; nevertheless, his very early insight into the physical relation of the sun to this problem had enabled him to discover the annual equation in the lunar motion, which he handled by modifying the equation of time.

Books V-VII of the *Epitome* dealt with practical geometrical problems arising from the elliptical orbits, the law of areas, and his lunar theory; and together with book IV they served as the theoretical explanation to the *Tabulae Rudolphinae*. Book V introduced what is now called Kepler's equation,

$$E = M - e \sin E,$$

where e is the orbital eccentricity, M is the mean angular motion about the sun, and E is an auxiliary angle related to M through the law of areas; Kepler named M and E the mean and the eccentric anomalies, respectively. Given E , Kepler's equation is readily solved for M ; the more useful inverse problem has no closed solution in terms of elementary trigonometric functions, and he could only recommend an approximating procedure. In the *Tabulae Rudolphinae*, Kepler solved the equation for a uniform grid of E values and provided an interpolation scheme for the desired values of M (see below).

Book VI of the *epitome* treated problems of the apparent motions of the sun, the individual planets, and the moon. The short book VII discussed precession and the length of the year. To account for the changing obliquity, Kepler placed the pole of the ecliptic on a small circle, which in turn introduced a minor variation in the rate of precession (one last remnant of trepidation); because he was not satisfied with the ancient observations, he tabulated alternative rates in the *Tabulae Rudolphinae*. Such problems, he proposed, could be left to posterity "if it has pleased God to allot to the human race enough time on this earth for learning these left-over things."³¹

Tabulae Rudolphinae. In his own eyes Kepler was a speculative physicist and cosmologist; to his imperial employers he was a mathematician charged with completing Tycho's planetary tables. He spent most of his working years with this task hanging as a burden as well as a challenge; ultimately it provided the chief vehicle for the recognition of his astronomical accomplishments. In excusing the long delay in publication, which finally took place in 1627, he mentioned in the preface not only the difficulties of obtaining his salary and of the wartime conditions but also "the novelty of my discoveries and the unexpected transfer of the whole of astronomy from fictitious circles to natural causes, which were most profound to investigate, difficult to explain, and difficult to calculate, since mine was the first attempt."³²

Although the rudiments of the tables must have been finished by 1616, when he calculated the first of the annual *Ephemerides* for 1617-1620, Kepler was still wrestling with the form of the lunar theory; in fact, the double-entry table for lunar evection ultimately determined the page size of the printed edition. But before he cast these tables in a final form, his project was overtaken by what he called a "happy calamity" — his initiation into logarithms.

Kepler had seen [John Napier's](#) *Mirifici logarithmorum canonis descriptio* (1614) as early as 1617; but he did not study the new procedure carefully until by chance, the following year, he saw Napier's tables reproduced in a small book by Benjamin Ursinus. Kepler then grasped the potentialities offered by the logarithms; but lacking any description of their construction, he re-created his own tables the by a new geometrical procedure. He tried to base his theory of logarithms on a Eudoxian theory of general proportion; but he could not resolve the problem of limit increments, which he concealed in the guise of numerical approximation. The form of his logarithms differed both from Napier's and from Briggs's; in modern notation Kepler's $\log x$ was

so that his $\log x = 10^5 \ln(10^5/x)$. His tables and theory were published in the *Chilias logarithmorum* (1624), and numerous examples of their use appeared in the *Supplementum . . .* (1625).

Unlike the *Ephemerides*, the *Tabulae Rudolphinae* did not contain sequential positions of planets for specified days; rather, it provided perpetual tables for calculating such positions for any date in the past or future. To compute the longitude for a particular planet on a specified date, the user must first find the mean longitude and the position of the aphelion by adding the appropriate angles from the mean motion tables for that planet to the starting positions tabulated for the beginning of the preceding century. The difference between the mean longitude and the aphelion angle is the mean anomaly, which is entered in the "Tabula aequationum" for the planet in question the user extracts from the table the true anomaly (called by Kepler the "anomaliam coequatam"), that is, the angle at the sun measured from the aphelion. The table in effect provides a tabulated solution of Kepler's equation coupled with the conversion from the eccentric anomaly to the true anomaly. (Kepler calls the term $e \sin E$ the "physical equation," and the remainder of the conversion the "optical equation.") It is here that he first exploited the logarithms, as an aid to interpolation. (As stated above in the discussion of the *epitome*, he solved his equation for a uniform grid of eccentric anomaly angles, which led to a set of nonuniformly from the interpolation, added to the aphelion angle, gives the heliocentric longitude.

Previous planetary tables yielded geocentric planetary positions directly from a single procedure. In Kepler's more exact version, the heliocentric positions of the earth and the planets are calculated separately and then combined to produce the geocentric position—essentially a problem in vector addition. Thus, the second important use of logarithms arose from this thoroughly heliocentric basis of the *Tabulae Rudolphinae*. Kepler tabulated the logarithms of the heliocentric distances and provided a convenient double-entry “Tabula Anguli” for combining the heliocentric longitudes into geocentric ones. He explained all these procedures, including the manipulation of logarithms, in a series of precepts that preceded the tables. There the ellipse was introduced, but for the full astronomical theory the reader was urged to consult the *Epitome*.

The *Tabulae Rudolphinae* gave planetary positions far more accurate than those of earlier methods; for example, the predictions for Mars previously erred up to 5° but Kepler's tables kept within $\pm 10'$ of the actual position. In calculating his *Ephemeris* for 1631, Kepler realized that the improved accuracy of his tables enabled him to predict a pair of remarkable transits of Mercury and of Venus across the disk of the sun. These he announced in a small pamphlet, *De raris mirisque anni 1631 phenomenis* (1629). Although he did not live to see his predictions fulfilled, the Mercury transit was observed by [Pierre Gassendi](#) in Paris on 7 November 1631; this observation, the first of its kind in history, was a tour de force for Kepler's astronomy, for his prediction erred by only 10' compared to 5† for tables based on Ptolemy, Copernicus, and others. (The transit of Venus in 1631 was not visible in Europe because it took place at night.)

The printed volume of the *Tabulae Rudolphinae* contains 120 folio pages of text in the form of precepts and 119 pages of tables. Besides the planetary, solar, and lunar tables and the associated tables of logarithms it includes Tycho Brahe's catalog of 1,000 fixed stars, a chronological synopsis, and a list of geographical positions. In some of the copies there is also a foldout map of the world, measuring 40x65 centimeter; the map was engraved in 1630 but apparently was not distributed until many years later. This work stands alone among Kepler's books in having an engraved frontispiece — filled with intricate baroque symbolism, it represents the temple of Urania, with the Tyconic system inscribed on the ceiling. Hipparchus, Ptolemy, Copernicus, and Tycho are at work within the temple, and Kepler himself is depicted in panel a below. The dome of the allegorical edifice is adorned with goddesses whose paraphernalia subtly remind the readers of Kepler's scientific contributions.

As with Kepler's other great books, the printing history of the tables was intricately linked with his personal odyssey. The material was ready for printing in 1624, but he believed that the Linz press was inadequate for this great work. Furthermore, his printer, Johannes Plank, intended to leave Linz because of the religious turmoil.

Since the tables were to be named after Rudolph, Kepler hoped to use their potential publication as leverage to collect 6,300 guldens in back pay. Consequently he spent the autumn of 1624 promoting his affairs at the imperial court in Vienna. Emperor Ferdinand II approved a scheme to impose the back payment on the cities of Nuremberg, Memmingen, and Kempten but insisted that the tables be printed in Austria. The following spring Kepler visited these cities; although he concluded satisfactory arrangements with the latter two towns, which supplied the paper for the printing, he never collected the 4,000 guldens imposed on Nuremberg. In order not to delay the work further, Kepler finally financed the printing from his own funds, even importing his own type for the numerical tables, a fact referred to on the final elaborate title page.

Barely had the typesetting begun when the Counterreformation struck Linz. Although Kepler received a concession for himself and his Lutheran printers to remain, the printing progressed very slowly. By the summer of 1626 Linz was blockaded, and Plank's house and press went up in flames. In a letter Kepler described his own circumstances:

You ask me what I have been doing during the long siege? First ask me what I have been *able* to do in the middle of the soldiers. It appeared to be a favor from the commissioner when a year ago I moved into a government house. This house lies along the city wall. All the towers had to be kept open for the soldiers, who by their going in and out disturbed my sleep by my studies by day. An entire reserve detachment settled in our house. The ear was incessantly exhausted by the noise of the cannons, the nose by the stench, the eye by the glare of fire.

Nevertheless, in these evil circumstances I myself undertook against Scaliger the same thing that our garrison undertook against the peasants. I have composed a splendid treatise on chronology. . . This pugnacious sort of writing wiped out for me much boredom from the inconveniences of the siege and impediments to work. If I had not happened upon this there would have been something else for me to do in making the tables more useful.³³

As soon as the siege was lifted, Kepler petitioned the emperor for permission to move to Ulm. Although he had worked in Linz longer than he had in any other place, the astronomer was glad to leave. He packed up his household, books, manuscripts, and type and traveled by boat up the Danube to Regensburg. After finding accommodations there for his wife and children on to Ulm, where the printing was soon under way. Kepler spent many hours supervising the typesetting in order to guarantee a neat, aesthetic result. By September 1627, the large edition of 1,000 copies was at last completed.

Last Years in Sagan and Regensburg. Even before the *Tabulae Rudolphinae* was printed, Kepler began to search for a new residence. Some years earlier he had dedicated his *Harmonice mundi* to James I; in 1619 the English poet [John Donne](#) visited him, and in 1620 the English ambassador [Sir Henry Wotton](#) had called on him in Linz and had invited him to England. To his Strasbourg friend Matthias Bernegger he confided, “Therefore shall I cross the sea, where Wotton calls me? I, a ?German? A lover of firm land, who dreads the confinement of an island?”³⁴ But in 1627 he wrote to Bernegger, “As soon as the

Rudolphines are published, I desire to find a place where I can lecture about them to a large audience, if possible in Germany, otherwise in Italy, France, Holland or England, provided the salary is adequate for traveler.”³⁵

Torn between his desire to find religious toleration and his reluctance to lose his salaries as provincial and imperial mathematician, Kepler journeyed to Prague at the end of 1627 to arrange further employment. Ferdinand III has just been crowned king of Bohemia; and the imperial commander-in-chief, Albrecht von Wallenstein, was at the height of his power. Ferdinand received Kepler graciously and awarded him 4,000 gulden (to be paid by Nuremberg and Ulm) for the dedication of the tables, but it was made clear that the astronomer should become a Catholic to remain in imperial service.

On the other hand, Wallenstein, a superstitious man who had earlier applied anonymously to Kepler for a horoscope, favored peaceful coexistence of the various creeds. The general had just received the duchy of Sagan as a fief and, anxious to raise the status of his new possession as well as to have close access to an astrologer, agreed to support both Kepler and a printing press there. Because Protestants were not yet restricted in Sagan, Kepler accepted. But he was unwilling to “let himself be used like an entertainer” and was reluctant to compromise his own scientific convictions to satisfy the “quite visibly erroneous delusion” of his astrologically minded patron. The general arranged everything to his satisfaction, however, by employing Kepler to calculate the precise positions and then obtaining the predictions from less inhibited astrologers.

Kepler collected his family in Regensburg, settled his affairs in Linz, and finally reached Sagan in July 1628. Apart from his ceaseless work, he found little of interest there. “I am a guest and stranger,” he complained to Bernegger, “almost completely unknown, and I barely understand the dialect so that I myself am considered a barbarian.”³⁶ Shortly after his arrival religious strife broke out, and for political reasons Wallenstein pressed Catholicism onto his subjects. Although Kepler was not personally affected, the persecutions made it difficult to attract printers there for the intended publication of Brahe’s observations. It took months to find a press and workmen, and Kepler himself acted as printer.

Eager to reap the fruits of his own astronomical tables, he set to work calculating ephemerides. In this he was assisted by Jacob Bartsch, a young scholar who had studied astronomy and medicine at Strasbourg and who calculated the positions for 1629-1636. *Ephemerides pars III* (for 1621-1639) was printed first, then the second part (for 1621-1629), which also contained Kepler’s daily weather observations. (The first part, for 1617-1620, had been printed year by year at Linz.)

At Sagan, Kepler finally began to print a short book of a far different sort, whose beginnings went back to his school days at Tiibingen: his *Somnium seu astronomia lunari*. The “Dream” is a curiously interesting tract for two reasons. First, its fantasy framework of a voyage to the moon made it a pioneering and remarkably prescient piece of [science fiction](#). Second, its perceptive description of celestial motions as seen from the moon produced an ingenious polemic on behalf of the Copernican system.

Kepler had written out the *Somnium* 1609, and copies circulated in manuscript. Because the work took the form of an interview with a knowledgeable “daemon” who explained how a man could be transported to the moon, there were overtones of witchcraft that later played an embarrassing role in his mother’s trial. Kepler himself remarked about this in one of the 223 notes that he added when he returned to the *Somnium* in 1621: “Would you believe that in the barber shops there was chatter about this story of mine? When this gossip was taken up by senseless minds, it flared up into defamation, fanned by ignorance and superstition. If I am not mistaken, you will judge that my family could have gotten along without that trouble for six years”³⁷—a clear reference to his mother’s legal entanglement between 1615 and 1621.

In Sagan, Kepler waited in vain for the payment of his salary claims, which had been transferred to Wallenstein. In June 1630, Ferdinand III summoned an electoral congress at Regensburg; and in August, Wallenstein lost his position as Commander-in-Chief. On 8 October the fifty-eight-year-old Kepler set out for Regensburg, taking with him all his books and manuscripts. Although his ultimate goal was Linz, where he hoped to collect interest on two Austrian district bonds, he must have intended to consult with the emperor and his court friends in Regensburg about a new residence. A few days after reaching Regensburg, Kepler became sick with an acute fever; the illness became worse, and on 15 November 1630 he died. He was buried in the Protestant cemetery; the churchyard was completely demolished during the thirty years war.

Jacob Bartsch, who had married Kepler’s daughter Susanna in March 1630, became a faithful protector of the bereaved and penniless family. He pressed on with the printing of the *Somnium*, and he tried in vain to collect the 12,694 gulden still owed by the state treasury. He recorded the epitaph that Kepler himself has composed:

*Mensus eram coelos, nunc terrae metior umbras:
Mens coelestis erat, corporis umbra jacet.*

I used to measure the heavens,
now I shall measure the shadows of the earth.
Although my soul was from heaven,
the shadow of my body lies here.

Evaluation. Kepler was a small, frail man, nearsighted, plagued by fevers and stomach ailments, yet nonetheless resilient. In his youth he had compared himself to a snappish little house dog who tried to win the favor of his masters but who drove

others away, but his later years in part belied this self-image. He never rid himself of a feeling of dependence, nor could he exhibit the imperious self-assurance of Tycho or of Galileo. Nevertheless, his ready wit, modest manner, and scrupulous honesty, as well as his wealth of knowledge, own him many friends. In the dedication to the *Epitome* he wrote, "I like to be on the side of the majority"; but in his Copernicanism and in his deep-felt religious convictions he learned the role of a staunch, lonesome minority.

Delambre has aptly summarized Kepler's persistent approach to scientific achievement:

Ardent, restless, burning to distinguish himself by his discoveries, he had glimpsed something, nothing was too hard for him in following or verifying it. All his attempts did not have the same success, and indeed that would have been impossible. . . . When in search of something that really existed, he sometimes found it ; when he devoted himself to the pursuit of a chimera, he could only fail; but even there he revealed the same qualities and that obstinate perseverance that triumphed over any difficulties that were not insurmountable.³⁸

Kepler's scientific thought was characterized by his profound sense of order and harmony, which was intimately linked with his theological view of God the Creator. He saw in the visible universe the symbolic image of [the Trinity](#). Repeatedly, he stated that geometry and quantity are coeternal with God and that mankind shares in them because man is created in the image of God. (In this framework Kepler can be called a mystic.) From these principles flowed his ideas on the cosmic link between man's soul and the geometrical configurations of the planets; they also motivated his indefatigable search for the mathematical harmonies of the universe.

contrasting with kepler's mathematical mysticism, and yet growing out of it through the remarkable quality of his genius, was his insistence on physical causes. Many examples illustrate his physical insight: his embryonic ideas of universal gravitation as articulated in the introduction to the *Astronomianova*; his trailblazing (but not fully correct) use of "inertia"; the statement "If the word *soul* is replaced by *force*, we have the very principle on which the celestial physics of the Mars Commentaries is based."³⁹ In Kepler's view the physical universe was not only a world of discoverable mathematical harmonies but also a world of phenomena explainable by mechanical principles.

Kepler wrote prolifically, but his intensely personal cosmology was not very appealing to the rationalists of the generations that followed. A much greater audience awaited a more gifted polemicist, Galileo, who became the persuasive purveyor of the new cosmology. Kepler was an astronomer's astronomer. It was the astronomers who recognized the immense superiority of the *Tabulag Rudolphinae*. For the Professional the improvement in planetary predictions was a forceful testimony to the efficacy of the Copernican system.

Tables copied after Kepler's were published by N. Durret (Paris, 1639), V. Renieri (Florence, 1639), J. B. Morin (Paris, 1650, 1657), M. Cunitz (Oels, 1650), H. Coley (London, 1675), N. Mercator (London, 1676), and T. Streete (1705); many others based ephemerides on Kepler's work. Use of the tables sometimes also generated an interest in the physical bases; Durret, for example, described both the elliptical orbits and an equivalent form of the law of areas. In England an early and influential disciple was [Jeremiah Horrocks](#); at the time of his early death in 1641, he was working on a book, published posthumously, that strongly supported Kepler's theories. Descartes apparently was ignorant of his work on planetary motions, but in 1642 [Pierre Gassendi](#) mentioned the ellipses and physical theories with apparent approval. In his *Astronomica Philolaica* (1645) Ismael boulliau accepted the elliptical orbit although he rejected Kepler's celestial physics.

Newton's early student notebooks show that he learned kepler's first and third laws from Streete's *Astronomia Carolina* (1661). The first author after Kepler to state all three of Kepler's laws was G. B. Riccioli in his *Almagestum novum* (1651); somewhat later Mercator did so in his *Institutionum astronomicarum* (1676). Isaac Newton's well-thumbed copy of this latter work was undoubtedly the source of his information about Kepler's second law, which played a crucial role in the development of his physics. Although nowhere in book I of the *Principia* is Kepler's name mentioned (Newton attributes the harmonic law to him in book III), the work was introduced to [Royal Society](#) as "a mathematical demonstration of the Copernican hypothesis as proposed by Kepler." Perhaps the most just evaluation of Kepler has come from [Edmond Halley](#) in his review of the *Principia*; Newton's first eleven propositions, he wrote, were "found to agree with the *Phenomena* of the Celestial Motions, as discovered by the great Sagacity and Diligence of kepler"⁴⁰

NOTES

KGW stand for [Johannes Kepler Gesammelte Werke](#); full references are found in the bibliography.

1. C. Firsch, Ed., *Kepleri opera omnia*, VIII, 671-672.

2. KGW., III, 108.

3. *Ibid.*, IV, 12

4. *Ibid.*, 253.

5. *Ibid.*, 1, 9 ff.
6. *Ibid.*, XIII, 40
7. J. L. E. Dreyer, *History of the Planetary Systems* p. 373.
8. E. Rosen, in [Johannes Kepler](#) *Werk and Leistung*, p. 148.
9. *KGW*, XIV, 130.
10. Frisch, ed., *op. cit.*, I, 240.
11. *KGW*, XIV, 203.
12. *Ibid.*, III, 156.
13. *Ibid.*, 178.
14. *Ibid.*, XIV, 410.
15. *Ibid.*, XV, 146.
16. *Ibid.*, I, 285.
17. *Ibid.*, IV, 519.
18. *Ibid.*, 293.
19. *Ibid.*, XIV, 327.
20. *Ibid.*, IV, 161.
21. *Ibis.*, XVII, 327.
22. *Ibis.*, 254.
23. M. Caspar, *Kepler* (1959), p. 290.
24. *KGW*, VI, 280.
25. *Ibid.*, VII, 297.
26. *Ibid.*, VI, 328.
27. *Ibid.*, 290.
28. J. L. Russell, "Kepler's Laws of Planetary Motion: 1609-1666."
29. *KGW*. XV, 136.
30. *Ibid.*, XVII, 187.
31. *Ibid.*, III, 408.
32. *Ibid.*, X, 42-43.
33. *Ibid.*, XVIII, 272-273.
34. *Ibid.*, 63.
35. *Ibid.*, 277-278.

36. *Ibid.*, 402.

37. E. Rosen, *Kepler's Somnium* p. 40.

38. J. B. J. Delambre, *Histoire de l'astronomie moderne*, I, 358.

39. *KGW*, VIII, 113.

40. E. Halley, in *Philosophical Transactions of the Royal Society*, no. 186 (1687), 291.

BIBLIOGRAPHY

Max Caspar's *Bibliographia Kepleriana* (Munich, 1936; rev. by Martha List, Munich, 1968) gives the definitive annotated listing of Kepler's printed works, later eds., and trans. It includes 574 secondary writings about Kepler to 1967. Since at least 100 articles and books were produced in connection with the 1971 anniversary, the following list is necessarily highly selective.

I. Original Works. A. **Printed Books.** *Joannis Kepleri astronomi opera omnia*, Christian, Frisch, ed., 8 vols. (Frankfurt-erlangen, 1858-1871; reprinted, Hildesheim, 1971-) includes all of the major printed works and also extensive excerpts from Kepler's correspondence, copious editorial notes, a 361-page Latin *vita*, and an index as yet unsurpassed. It contains the initial publication of, and is still the only printed source for, the "Apologia Tychonis contra Nicolaum Ursum," "Hippachus," and other MSS; these are listed by Caspar, *op. cit.*, pp. 111-113.

In the twentieth century a monumental Kepler opera was planned by Walther von Dyck and Max Caspar and carried out under the auspices of the Deutsche Forschungsgemeinschaft and the Bayerische Akademie der Wissenschaften; Caspar and Franz Hammer have served successively as eds. The extensive notes and commentaries make this ed. the single most valuable source for any Kepler scholar. As now envisioned, the *Johannes Kepler Gesammelte Werke* (Munich, 1937-) will encompass 22 vols. when complete. Concerning this edition see Franz Hammer, "Problems and Difficulties in Editing Kepler's Collected Works," in *Vistas in Astronomy*, 9 (1967), 261-264. An abridged table of contents, with short titles and the dates of original publication, is given here for reference: I, *Mysterium cosmographicum* (1596), *De stella nova* (1606); II, *Additamentum ad vitellionem paralipomena* or *Astronomiae pars optica* (1604); III, *Astronomianova* (1609); IV, *Phaenomenon singulare* (1609), *Tertius interveniens* (1610), *strena* (1611), *Dissertation cum Nuncio sidereo* (1610), *Dioptrice* (1611); V, *De vero anno* (1614), *Bericht vom Geburtsjahr Christi* (1613), *Eclogae chronicae* (1615); VI, *Harmonice mundi* (1619); VII, *Epitome astronomiae copernicanae* (1618-1621); VIII, *Mysterium cosmographicum* (1621), *De cometis libelli tres* (1619), *Hyperaspistes* (1625); IX, *Nova stereometria doliorum vinariorum* (1615), *Messekunst Archimedis* (1616), *Chilias logarithmorum* (1624); X, *Tabulae Rudolphinae* (1627); XI, *Ephemerides novae* (1617-1619), *Ephemerides* (1630), and the small calendars; XII, *Somnium* (1634), theological writings, and trans; XIII-XVIII, letters, in chronological order; XIX, documents; XX-XXII, synopsis of the MS material, and index.

Except for the two collected eds., Kepler's works have been reprinted rather rarely; most of the other reprinting occurred in connection with the greater interest in Galileo: *dioptrice* (London, 1653, 1683); *dissertatio cum nuncio sidereo* (Modena, 1818; Florence, 1846, 1892); *Perioche ex introductione in Martem* (Strasbourg, 1635; London, 1641, 1661 [in English], 1663; Modena, 1818; Florence, 1846). Recent facsimiles include *Dioptrice* (Cambridge, 1962); *dissertation cum Nuncio sidereo* (Munich, 1964); *Astronomianova*, *Harmonice mundi*, and *Astronomiae pars optica* (Brussels, 1968); and *Somnium* (Osnabrück, 1969).

Nor have trans. been frequent. Outstanding exceptions are the three published in German by Max Caspar: *Das Weltgeheimnis (Mysterium cosmographicum)* (Augsburg, 1932; Munich-Berlin, 1936; *New Astronomie* (Munich-Berlin, 1929); *Weltharmonik* (Munich-Berlin, 1939; repr. 1967). In addition, Caspar and Walther von Dyck published *Johannes Kepler in seinen Briefen*, 2 vols. (Munich-Berlin, 1930); this served as the basis for Carol Baumgardt, *Johannes Kepler: Life and Letters* (New York, 1951). See also *Johannes Kepler—Selbstzeugnisse*, sel. by Franz Hammer and trans. by Esther Hammer (Stuttgart-Bad Cannstatt, 1971).

The chief English trans. are the secs. of the *Epitome* (bks. IV and V) and the *Harmonice* (bk. v), prep. by Charles Glenn Wallis for Great Books of the Western World, XVI (Chicago, 1952). Several smaller works have been trans. in full, including John Lear, ed., *Kepler's Dream*, trans. by Patricia Frueh Kirkwood (Berkeley, 1965); Edward Rosen, *Kepler's conversation With Galileo's Sidereal Messenger* (New York, 1965); and *Kepler's Somnium* (Madison, Wis., 1967); and Colin Hardie, *The Six-Cornered Snowflake* (Oxford, 1966). An English trans. of the *Astronomianova* by Owen Gingerich and Ann Wegner Brinkley is nearing completion. Extended quotations from the *Astronomianova* are available in French in Alexander Koye, *La révolution astronomique* (Paris, 1961) and in its English trans. by E. W. Maddison (Paris, 1972).

B. Manuscripts. The thousands of MS sheets left at Kepler's death went to his son Ludwig, who promised publication but lacked both the time and the scientific knowledge for the undertaking. After Ludwig's death the Danzig astronomer [Johannes Hevelius](#) acquired the collection and published a brief inventory in *Philosophical Transactions of the Royal Society* 9 (1674),

29-31. In 1707 Michael Gottlieb Hansch obtained the material with the intention of publishing it, and in 1718 he produced *Joannis Kepleri aliorumque epistolae mutuae*, a large folio vol. containing 77 letters by Kepler and 407 to him. Hansch had the MSS bound in vellum in 22 vols., which he cataloged briefly in *Acta eruditorum*, no. 57 (1714), 242-246; in 1721 financial difficulties forced him to pawn 18 of the vols. The other four— VII, VIII, and XII, which had formed the basis for his *Epistolae*, and VI, which was used for *De calendario Gregoriano* (Frankfurt, 1726)—eventually found their way to the Osterreichische Nationalbibliothek in Vienna, where VI is codex 10704 and the three original vols. of letters have apparently been rebound into codices 10702 and 10703. Not until about 1765 were the 18 vols. rediscovered, and in 1773 [Catherine II](#) purchased them for the Academy of Sciences in [St. Petersburg](#). They are still preserved in Leningrad. details of this odyssey are chronicled by Martha List. *Der handschriftliche Nachlass der Astronomen Johannes Kepler and Tycho Brahe* (Munich, 1961).

The 18 Leningrad **MS** vols. contain roughly the following: I, the unfinished “Hipparchus” dealing with planetary and especially lunar theory, partially published by Firsich (*op. cit.*, III); II, lunar theory and tables; III, nova of 1604, including letter; IV, musical theory, including notes to Vincenzo Galilei’s *Dialogo della musica antica e della moderna* and Kepler’s trans. of bk. III of Ptolemy’s *Libri harmonicorum*; V, geometry, studies of Euclid, “Apologia Tychonis” [VI-VIII, XII, in Vienna]; IX-XI, letters; XIII, motion of Mercury, Venus, Jupiter, Saturn; XIV, workbook on Mars, dating from 1600-1601, plus early drafts of some chs. of *Astronomianova* XV, observations and theory of solar and lunar eclipses; XVI, “Chronologia ab origine rerum usque ad annum ante Christum”; XVII, chronological notes on Scaliger and Petavius, German trans. and annotations of ch. 13 from Aristotle’s *De caelo* bk. II, on the position and shape of the earth; XVIII, horoscopes, examination of observations of Regiomontanus and Berthard Walther; XIX, length of year, Greek astronomy, horoscopes; XX. MS printer’s copy of the *Tabulae Rudolphinae*; XXI, Biblical chronology, including three tracts published by Frisch (*op. cit.*, VII).

From 1839 to 1937 the **MSS** were housed at the Pulkovo observatory, and during that time they were made available to Frisch and to Duck and Caspar for the preparation of the two eds. Unfortunately, some of the material copied by Frisch is no longer to be found, for example, part of the remarkable “self-analysis” formerly in XXI. At the Royal Observatory in Edinburgh is a page of a Kepler letter given to Lord Lindsay when he visited the Pulkovo observatory, and undoubtedly other leaves were dispersed in a similar manner. A complete set of photocopies of the currently available pages (together with photographs of virtually all the other known Kepler MSS is found at the Kepler Commission of the Bavarian Academy of Sciences at the Deutsches Museum in Munich. Secondary sets are located at the Württembergische Landesbibliothek in Stuttgart and at the Bayerische Staatsbibliothek in Munich.

Besides the four vols. already mentioned, many additional MSS are found in Vienna, especially with the Tycho Brahe material in codices 10686-10689. These are listed, rather unreliably, in *Tabulae codicum manu scriptorum. . . in Bibliotheca palatina Vindobonensi asservatorum*, VI (Vienna, 1871). The third most important repository of Kepler MSS is the Württembergische Landesbibliothek in Stuttgart, with about 60 letters and some notes; in addition, the Hauptstaatsarchiv in Stuttgart contains rich documentation on the witchcraft trial of Kepler’s mother. Some of the latter material was published by Frisch (*op. cit.*, VIII). Other significant collections, especially of letters, are in Oxford, Munich, Graz, Paris, Florence, Wolfenbüttel, and Tübingen.

Some of the letters were originally printed in the Nova Kepleriana series in the *Abhandlungen der Bayerischen Akademie der Wissenschaften* (1910-1936); a new series is continuing the publication of other **MS** material (Munich, 1969-), beginning with Jürgen Hübener’s ed. of *Unterricht vom h. Sacrament*.

Kepler’s rather sparsely annotated copy of Copernicus’ *De revolutionibus*, now in the Leipzig University Library, has been reproduced in facsimile (Leipzig, 1965).

II. Secondary Literature. Still useful among many early biographical accounts are John Drinkwater Bethune, *Life of Kepler* (London, 1830), a pamphlet in the Library of Useful Knowledge and later in the *Penny Cyclopaedia* (London, 1839); Edmund Reitlinger’s uncompleted *Johannes Kepler* (Stuttgart, 1868); and Christian Frisch, “Kepleriviv,” in his *Kepleri opera omnia*, VIII (Frankfurt, 1817), 668-1028. The standard biography by Max Caspar, C. Dris Hellman (New York, 1959), is based on an extensive familiarity with the sources, including the letters; from a scholarly viewpoint, its lack of citations and its inadequate index are disappointing. [Arthur Koestler](#), *The Sleepwalkers* (New York, 1959), is a compellingly written account with an emphasis in the psychology of discovery; the part specifically on Kepler has been published separately in an expurgated version, *The Watershed* (New York, 1960).

Two particularly well-illustrated books are Walther Gerlach and Martha List, *Johannes Kepler, Dokument zu Lebenszeit and Lebenswerk* (Munich, 1971); and Justus Schmidt, *Johann Kepler, sein Leben in Bildern and eigenen Berichten* (Linz, 1970).

The quadricentennial of Kepler’s birth in 1971 provided the occasion for several collections of papers; the contents of these are listed and selected papers reviewed by Robert S. Westman, “Continuities in Kepler Scholarship: The European Kepler Symposia, 1971, in *Historiographical Perspective*.” This paper, together with the others presented at a symposium in Philadelphia, is found, edited by Arthur Beer, in *Vistas in Astronomy*, **18** (1975). Thirteen papers appear in the catalog for the Kepler exhibition at Linz organized by Wilhelm Freh, *Johannes Kepler, Werk and Leistung*, Katalog des Oberösterreichischen Landesmuseums no. 74, Katalog des Stadtmuseums Linz no. 9 (Linz, 1971). Papers on “little-known aspects of Kepler” appear in Firtz Krafft, Krafft, Karl Meyer, and Bernhard Sticker, eds., *Internationales Kepler-Symposium Weil der Stadt 1971*, Beiträge zur Wissenschaftsgeschichte, ser. A, I (Hildesheim, 1972). Twelve papers appear in Ekkehard Preuss, ed., *Kepler*

Festschrift 1971 (Regensburg, 1971), sponsored by the Naturwissenschaftlichen Verein Regensburg as a successor to Karl Stökl, ed., *Kepler Festschrift* (Regensburg, 1930). Papers presented at the International Union for the History and Philosophy of Science's International Kepler symposium in Leningrad will be published both in a Russian ed. and in western languages, edited by Arthur Beer, in *Vistas in Astronomy*, **18** (1975).

Three outstanding review papers given at these symposia are Walther Gerlach, "Johannes Kepler, Leben, Mensch und Werk" (Leningrad); Edward Rosen, "Kepler's Place in the History of Science" (Philadelphia); and I. Bernard Cohen, "Kepler's Century" (Philadelphia).

The printing history of Kepler's work is presented in Friedrich Seck, "Johannes Kepler und der Buchdruck," in *Archiv für Geschichte des Buchwesens*, **11** (1971), 610-726.

An early post-Newtonian appreciation and critique of Kepler is David Gregory, *Astronomiae physicae et geometricae elementa* (Oxford, 1702); the rev. English ed. of 1726 has been reprinted (New York, 1972). A succinct discussion of Kepler's astronomical achievements is found in J. L. E. Dreyer, *History of the Planetary Systems From Thales to Kepler* (Cambridge, 1906; repr. New York, 1953). An earlier account is E. F. Apelt, *Johann Kepler's astronomische Weltansicht* (Leipzig, 1849).

For fuller details, one must turn to more technical analyses such as Robert Small, *An Account of the Astronomical Discoveries of Kepler* (London, 1804; repr. Madison, Wis., 1963); and J. B. J. Delambre, *Histoire de l'astronomie moderne* (Paris, 1821), I, 314-615. These writers were interested in Kepler's techniques, not his philosophical foundations; and they were frequently embarrassed by his metaphysical reasoning—in fact, Small's chapter-by-chapter account of the *Astronomianova* completely omits ch. 57, on the magnetic forces underlying Kepler's formulation. For a more sympathetic treatment of the technical aspects of Kepler's laws within the framework of the metaphysical background, see Alexander Koyré, *La révolution astronomique* (Paris, 1961), pp. 119-458; Curtis Wilson, "Kepler's Derivation of the Elliptical Path," in *Isis* **59** (1968), 5-25; E. J. Aiton, "Kepler's Second Law of Planetary Motion," *ibid.*, **60** (1969), 75-90; and Owen Gingerich, "Johannes Kepler and the New Astronomy," in *Quarterly Journal of the Royal Astronomical Society*, **13** (1972), 346-373; and "The Origins of Kepler's Third Law," Leningrad Kepler Symposium, 1971. See also E. J. Aiton, *The Vortex Theory of Planetary Motions* (London, 1972), ch. 2, pp. 12-19; and Curtis Wilson, "How Did Kepler Discover His First Two Laws?," in *Scientific American*, **226** (Mar. 1972), 92-106.

Analyses of Kepler's planetary tables are Owen Gingerich, "A Study of Kepler's Rudolphine Tables," in *Actes du XI Congrès international d'histoire des sciences*, **III** (Wrocław, 1968), 31-36; Volker Bialas, "Die Rudolphinischen Tafeln von Johannes Kepler," in *Nova Kepleriana*, n.s. **2** (1969); and "Jovialia, Die Berechnung der Jupiterbahn nach Kepler," *ibid.*, n.s. **4** (1971); see also Owen Gingerich, "Johannes Kepler and the Rudolphine Tables," in *Sky and Telescope*, **42** (1971), 328-333. The impact of Kepler's tables and laws on subsequent astronomers has been described by J. L. Russell, "Kepler's Laws of Planetary Motion: 1609-1666," in *British Journal for the History of Science*, **2**, no. **5** (1964), 1-24; and by Curtis Wilson, "From Kepler's Laws, So-called, to Universal Gravitation: Empirical Factors," in *Archive for History of Exact Sciences*, **6** (1970), 89-170.

Other aspects of Kepler's astronomy are found in J. A. Ruffiner, "The Curved and the Straight: Cometary Theory From Kepler to Hevelius," in *Journal for the History of Astronomy*, **2** (1971), 178-194; A. Koyré, "Johannes Kepler's Rejection of Infinity," in his *From the Closed World to the Infinite Universe* (Baltimore, 1957), ch. 3, pp. 58-87; and Victor E. Thoren, "Tycho and Kepler on the Lunar Theory," in *Publications of the Astronomical Society of the Pacific*, **79** (1967), 482-489.

An awareness of Kepler as a philosopher of science, and of the unitary nature of his thought, is found in [Ernst Cassirer](#), *Das Erkenntnisproblem in der Philosophie und Wissenschaft der neuen Zeit*, I (Berlin, 1906), 328-377. See also Shmuel Sambursky, "Kepler in Hegel's Eyes," in *Proceedings of the Israel Academy of Sciences and Humanities*, **5** (1971), 92-104.

A seminal critique of the metaphysical foundations of Kepler's scientific concepts is Gerald Holto, "Johannes Kepler's Universe: Its Physics and Metaphysics," in *American Journal of Physics*, **24** (1956), 340-351. See also E. J. Dijksterhuis, *De Mechanisering van het Wereldbeeld* (Amsterdam, 1950); German trans. by H. Habicht (Berlin, 1956); English trans. by C. Dikshoorn (Oxford, 1971), pp. 337-359; Max Jammer, *Concepts of Force* (Cambridge, Mass., 1957), pp. 81-93; and Fritz Krafft, "Kepler's Beitrag zur Himmelsphysik," in *Internationales Kepler-Symposium, Weil der Stadt 1971* (Hildesheim, 1972).

Aspects of the intellectual background of Kepler are discussed by Harry A. Wolfson, "The Problem of the Souls of the Spheres From the Byzantine Commentaries on Aristotle. . . to Kepler," in *Dumbarton Oaks Papers*, **16** (1962), 67-93; J. O. Fleckenstein, "Kepler and Neoplatonism," in *Vistas in Astronomy*, **18** (1975); Robert Westman, "The Comet and the Cosmos: Kepler, Maästlin and the Copernican Hypothesis," in *Studia Copernicana* (Warsaw, in press); and K. Hujer, "Kepler in Prague—1600-1612," Leningrad Kepler Symposium, 1971.

Kepler's methodology is discussed by Robert Westman, "Johannes Kepler's Adoption of the Copernican Hypothesis" (doctoral diss., Univ. of Michigan, 1971); and "Kepler's Theory of Hypothesis and the 'Realist Dilemma,'" in *Internationales Kepler-Symposium, Weil der Stadt 1971* (Hildesheim, 1972). In the Weil der Stadt symposium, see also J. Mittelstrass, "Wissenschaftstheoretische Elemente der Keplerschen Astronomie"; and G. Buchdahl, "Methodological Aspects of Kepler's Theory of Refraction." These last three papers are also repr. in *Studies in History and Philosophy of Science*, **3** no. 3 (1972).

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For Kepler's musical harmonies, see D. P. Walker, "Kepler's Celestial Music," in *Journal of the Warburg and Courtauld Institutes.*, **30** (1967), 228-250; Eric Werner "The Last Pythagorean Musician; Johannes Kepler," in *Aspects of Mediaeval and Renaissance Music*, Jan La Rue, ed. (New York, 1966), pp. 867-882; and Michael Dickreiter, "Dur und Moll in Keplers Musiktheorie," in *Johannes Kepler, Werk und Leistung* (Linz, 1971), pp. 41- 50. See also Ulrich Klein, "Johannes Kepler' Bemühungen um die Harmonieschriften des Ptolemaios und Porphyrios," *ibid.*, pp. 51-60; and Francis Warrain, *Essai sur l'Harmonice mundi*, Actualités Scientifiques et Industrielles no. 912 (Paris, 1942). [Paul Hindemith](#) wrote a five-act opera based on Kepler's *life*, *Die Harmonie des Welt* (text: Mainz, 1957).

For Kepler's mysticism and astrology, see W. Pauli, "Der Einfluss archetypischer Vorstellungen auf die Bildung naturwissenschaftlicher Theorien bei Kepler," in *Natureklärung und Psyche* (Zurich, 1952), 109-194, trans. by Priscilla Silz as "The Influence of Archetypal Ideas on the Scientific Theories of Kepler," in *The Interpretation of Nature and the Psyche*, Bollingen Series, **51** (New York, 1955), 147-240; Franz Hammer, "Die Astrologie des Johannes Kepler," in *Sudhoffs Archiv*, **55** (1971), 133-135; and Arthur Beer, "Kepler' Astrology and Mysticism," in *Vistas in Astronomy*, **16** (1973). See also Marth List, "Das Wallenstein-Hisroskop von Johannes Kepler," in *Johannes Kepler, Werk und Leistung* (Linz, 1971), pp. 127-136.

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