

# Johannes Kepler and the New Astronomy

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Johannes Kepler was conceived on the 16th of May 1571 at 4.37 a.m. and born on the 27th of December at 2.30 p.m. We therefore see that 1971 was the 400th anniversary not only of Kepler's birth but also of his conception. The existence of such accurate dates reminds us that Kepler lived in an age when astronomer still meant astrologer and when the word 'scientist' had not yet been invented. Kepler wrote down these dates when he was 25 years old and much fascinated by astrology. Like many of the world's greatest scientists, he had a profound feeling for the harmony of the heavens; Kepler believed in a powerful concord between the cosmos and the individual, although he rejected many of the traditional details of astrology.

From our own scientific and philosophical vantage point far removed from the turn of the 17th century, any assessment of this man's genius must be incomplete and imperfect. Nevertheless, our 20th-century perspective can offer insights overlooked by the interpreters of previous generations. If Kepler could have chosen from our 20th-century words, I suppose that he would have called himself a cosmologist. I should like to argue that we can accurately call Kepler the first astrophysicist.

Kepler stands at a junction in the history of astronomy when the old Earth-centred Universe was giving way to the new Sun-centred system. Yet the heliocentric system as presented by Copernicus contained many vestiges of the old astronomy. Kepler's greatest book was the *Astronomia Nova*. Published in 1609, it broke the two-millennium spell of perfect circles and uniform angular momentum—it was truly the 'New Astronomy'. It is this work, which Kepler called his 'warfare on Mars', that will form the focus of my remarks.

There was little in Kepler's youth to indicate that he would become one of the foremost astronomers of all time. Although Tycho's supernova of 1572 burst forth when Kepler was a mere infant, the Great Comet of 1577 made a lasting impression. Kepler was a weak and sickly

child, but intelligent, and after the elementary Latin school he easily won a scholarship to the nearby Tübingen University so that he could study to become a Lutheran clergyman. There he produced a 'straight A' record—but the grade records preserved at Tübingen show that nearly everyone was an A student in 1589. In recommending him for a scholarship renewal, the University Senate noted that Kepler had 'such a superior and magnificent mind that something special may be expected of him'.

Yet Kepler himself wrote that although he had done well in the prescribed mathematical studies, nothing indicated to him a special talent for astronomy. Hence, he was surprised and distressed when, midway through his third and last year as a theology student at Tübingen, he was summoned to Graz, far away in southern Austria, to become an astronomy teacher and the provincial mathematician.

At the Protestant high school in Graz, Kepler turned out not to be a very good teacher. In the first year he had only a few students, in the second none at all. Needless to say, this gave him more time to pursue his own research! Nevertheless, it was in one of his class lectures that Kepler hit upon what he believed to be the secret key to the construction of the Universe.

This key hung upon a crucial thread: at Tübingen, Kepler had become a Copernican. The astronomy teacher at the University, Michael Maestlin, was remarkably knowledgeable about Copernicus's *De Revolutionibus*. Yet, strangely enough, his popular and often-reprinted textbook, *Epitome Astronomiae*, never even hinted at the heliocentric cosmology. Nevertheless, in his lectures at Tübingen, Maestlin included a discussion of the new Copernican system. He explained how this system accounted for the retrogradations in a most natural way, and how the planets were laid out in a very harmonic fashion, both with respect to their spacing from the Sun and with respect to their periods.

It was undoubtedly the beautiful harmonic regularities 'so pleasing to the mind' that appealed strongly to Kepler's sense of the aesthetic and induced him to become such an enthusiastic Copernican—as opposed to Maestlin, the timid Copernican. To Kepler the theologian, such regularities revealed the glory of God. When he finally hit upon that secret key to the Universe, he attributed it to Divine Providence. 'I believe this', he wrote, 'because I have constantly prayed to God that I might succeed in what Copernicus had said was true' (1). Later, in writing to his teacher Maestlin, he said, 'For a long time I wanted to become a theologian; for a long time I was restless. Now, however, behold how through my effort God is being celebrated in astronomy' (2).

Because of his preoccupation with the Copernican system, Kepler began to ask himself three unusual questions: Why are the planets

spaced this way? Why do they move with these regularities? Why are there just six planets? All these questions are very Copernican, the last one particularly so because a traditional geocentrist would have counted both the Sun and the Moon, but not the Earth, thereby listing seven planets.

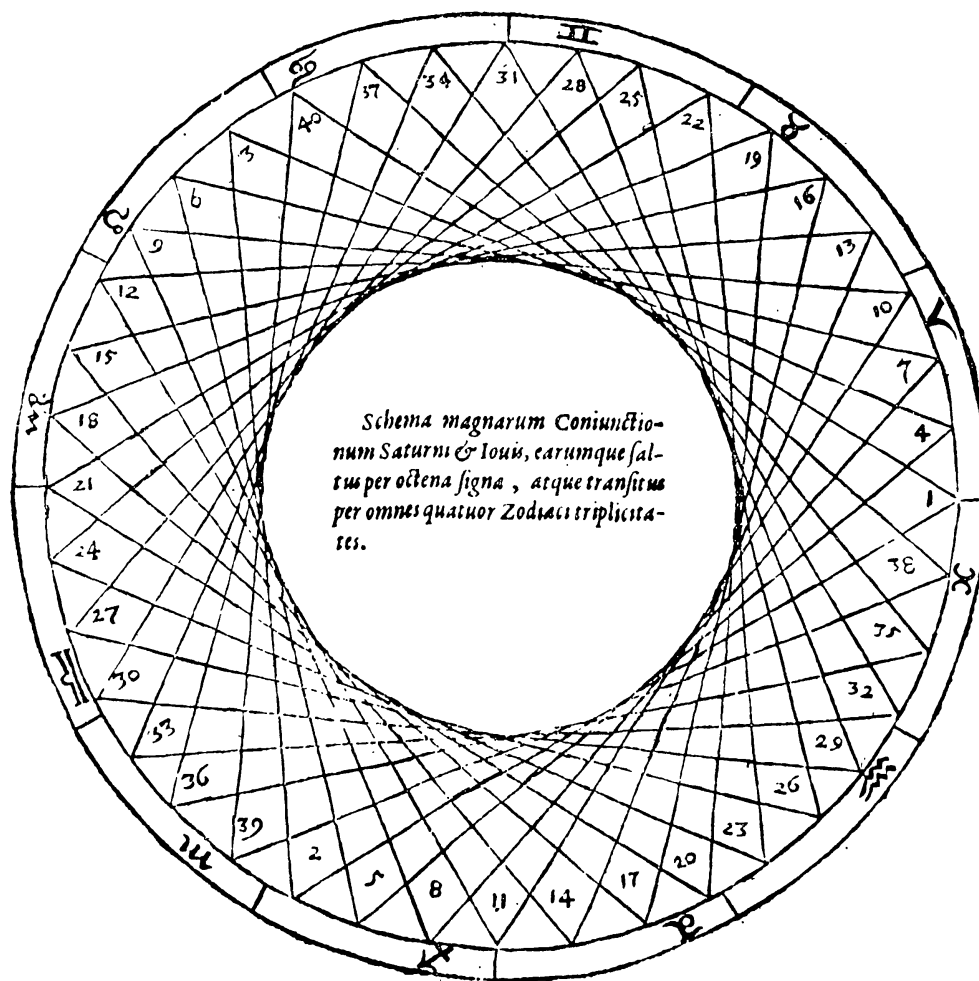


FIG. 1. The pattern of successive conjunctions of Jupiter and Saturn, from the *Mysterium Cosmographicum*.

Fig. 1 recalls the circumstances under which Kepler hit upon his secret key to the Universe. In a lecture to his class, he had drawn the ecliptic circle and he was illustrating how the great conjunctions of Jupiter and Saturn, which take place every 20 years, fall almost one-third of the way around the sky in successive approaches. As he connected the successive conjunctions by quasi-triangles, the envelope of lines outlined a circle with a radius half as large as that of the outer ecliptic circle. The proportion between the circles struck Kepler's eye as almost identical with

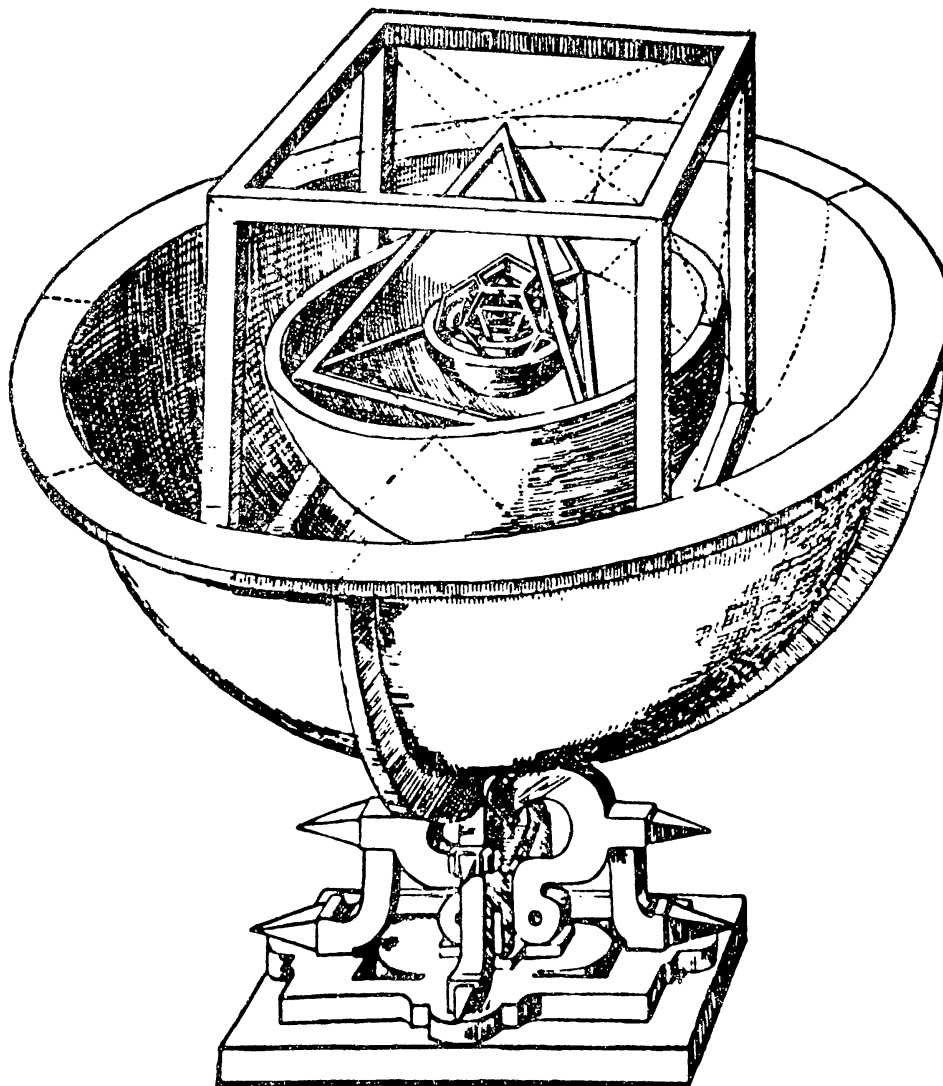


FIG. 2. The nesting of regular polyhedra and planetary spheres that accounted for the spacing and number of planets according to Kepler. Adapted from his *Mysterium Cosmographicum*.

the proportions between the orbits of Saturn and Jupiter. Immediately he began a search for a similar geometrical relation to account for the spacing of Mars and the other planets, but his quest was in vain.

‘And then again it struck me’, he wrote. ‘Why have plane figures among three-dimensional orbits? Behold, reader, the invention and the whole substance of this little book!’ (3). He knew that there were five regular polyhedra, that is, solid figures each with faces all the same kind of regular polygon. By inscribing and circumscribing these figures with spheres (all nested in the proper order), he found that the positions of the spheres closely approximated the spacings of the planets (Fig. 2).

Since there are five and only five of these regular or Platonic polyhedra, Kepler thought that he had explained the reason why there were precisely six planets in the solar system.

Kepler published this scheme in 1596 in his *Mysterium Cosmographicum*, the 'Cosmographic Secret'. It was the first new and enthusiastic Copernican treatise in over 50 years, since *De Revolutionibus* itself. Without a Sun-centred Universe, the entire rationale of the book would have collapsed.

Kepler also realized that the centre of the Copernican system was the centre of the Earth's orbit, not the Sun. Although the Sun was nearby, it played no physical role. But Kepler argued that the Sun's centrality was essential and that the Sun itself must supply the driving force to keep the planets in motion. Not only did he propose this very significant physical idea, but he attempted to describe mathematically how the Sun's driving force diminished with distance. Again, his result was only approximate, but at least the important physical-mathematical step had been taken. This idea, which was to be much further developed in the *Astronomia Nova*, establishes Kepler as the first scientist to demand physical explanations for celestial phenomena. Although the principal idea of the *Mysterium Cosmographicum* was erroneous, never in history has a book so wrong been so seminal in directing the future course of science.

Kepler sent a copy of his remarkable book to the most famous astronomer of the day, Tycho Brahe. Unknown to Kepler, the renowned Danish astronomer was in the process of leaving his homeland. He had boasted that his magnificent Uraniborg Observatory had cost the king more than a ton of gold. Now, however, fearing the loss of royal support, Tycho had decided to join the court of Rudolph II in Prague. Emperor Rudolph was a moody, eccentric man whose love of the occult made him more than willing to support a distinguished astronomer-astrologer.

Kepler describes this sequence of events in the *Astronomia Nova* itself. The Danish astronomer had been impressed by the *Mysterium Cosmographicum*, though he was unwilling to accept all its strange arguments; then, Kepler writes, 'Tycho Brahe, himself an important part in my destiny, continually urged me to come to visit him. But since the distance of the two places would have deterred me, I ascribe it to Divine Providence that he came to Bohemia. I arrived there just before the beginning of the year 1600 with the hope of obtaining the correct eccentricities of the planetary orbits. Now at that time Longomontanus had taken up the theory of Mars, which was placed in his hands so that he might study the Martian opposition with the Sun in  $9^\circ$  of Leo [that is, Mars near perihelion]. Had he been occupied with another planet, I



would have started with that same one. That is why I again consider it an effect of Divine Providence that I arrived in Prague at the time when he was studying Mars; because for us to arrive at the secret knowledge of astronomy, it is absolutely necessary to use the motion of Mars; otherwise that knowledge would remain eternally hidden' (4).

Kepler's *Astronomia Nova* was not to be published until nine years later. Never had there been a book like it. Both Ptolemy in the *Almagest* and Copernicus in *De Revolutionibus* had carefully dismantled the scaffolding by which they had erected their mathematical models. Although Kepler's book is well organized, it is nearly an order of magnitude more complete and complex than anything that had gone before; our astronomer himself admits that he might have been too prolix.

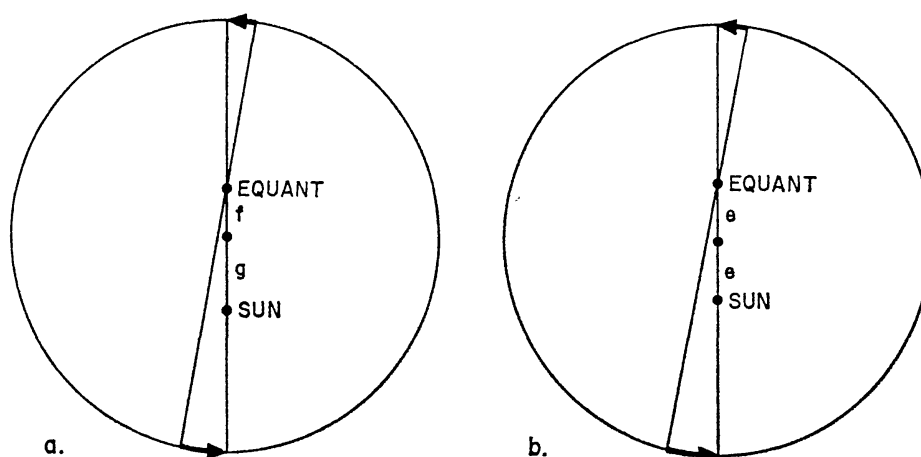


FIG. 3. The orbit of Mars with an equant, the seat of uniform angular motion. In the vicarious hypothesis (a), accurate longitudes are obtained by setting  $g/f = 5/3$ . The quasi-Ptolemaic scheme (b) with its equal-and-opposite equant satisfies the Sun–Mars distances but errs in longitude by  $8'$  in the octants.

In the first great battle in his warfare on Mars, Kepler describes the so-called vicarious hypothesis. This was an attempt to represent the motions of Mars on an eccentric circle driven by uniform angular motion about a point called an equant—essentially a traditional model cast into the new heliocentric pattern. Kepler achieved the great accuracy in the longitudes by allowing the equant to fall at an arbitrary position, as shown in Fig. 3 (a). In this scheme, which he was to call the 'vicarious hypothesis', the true anomaly is (neglecting terms in  $e^3$ ):

$$v = T - 2(f+g) \sin T + g \frac{(f+g)}{2} \sin 2T + \dots, \quad (I)$$

where  $g$  is the eccentricity from the Sun to the centre of the circle, and  $f$  is the eccentricity from the equant to the centre. For comparison, the motion in an ellipse with the law of areas is

$$v = T - 2e \sin T + \frac{5}{4} e^2 \sin 2T + \dots$$

Hence, if  $g = 5/4 e$  and  $f = 3/4 e$ , the vicarious hypothesis satisfies the equations to second order and we can show that the remaining error is approximately  $1/4 e^3$ , which, in the case of Mars with its eccentricity of nearly 0.1, amounts to about 1'. Thus, in predicting the longitudes, Kepler succeeded brilliantly, with an accuracy almost 2 orders of magnitude better than that of either Ptolemy or Copernicus.

There exists among Kepler's manuscript pages still preserved in Leningrad a remarkable sheet showing a diagram of the vicarious orbit (Plate V) (5). It is very carefully laid out in a publishable form as one of the first few pages of a book on Mars, and it includes the opening lines of the poetic tribute to Tycho that ultimately appeared in the *Astronomia Nova*. The diagram, with its unequally spaced equant in the ratio 5:3, can be seen at the bottom of the page. Kepler was always very eager to publish, and elsewhere in the manuscript material we see the titles for chapters in a book that he was organizing before he even knew that Mars had a non-circular orbit. Apparently, this page comes from about the same period—evidently at one point he was prepared to publish his vicarious orbit as the solution of the riddle of Mars. Fortunately, Divine Fate prevented him from publishing his commentary on Mars until it was truly the New Astronomy.

Although Kepler's scheme had achieved a great triumph with respect to the longitudes, it failed with respect to distances. In observational astronomy, longitudes can be determined directly with great precision, but in general the distances must be deduced by other methods. Here Kepler very cleverly used the latitudes of Mars to deduce the distances—but alas, this led to an absurdity and showed that his orbit could not, in fact, be the real one. Hence, he named it the vicarious orbit in contradistinction to the real or 'physical' hypothesis that he was seeking.

Ptolemy, in his orbit for Mars, had constrained the equant to fall directly opposite the centre of the orbit from the Earth and equally distant from it. Kepler now realized that such an equal-and-opposite equant more closely approximated the real orbit than did his vicarious orbit, which satisfied the longitude so well. This case is represented by equation (1) when  $e = f = g$ , or

$$v = T - 2e \sin T + e^2 \sin 2T + \dots,$$

so that the error in heliocentric longitude is  $1/4 e^2 \sin 2T$ ; in the case of Mars, this gives 8' in the octants, an error easily detectable with Tycho's

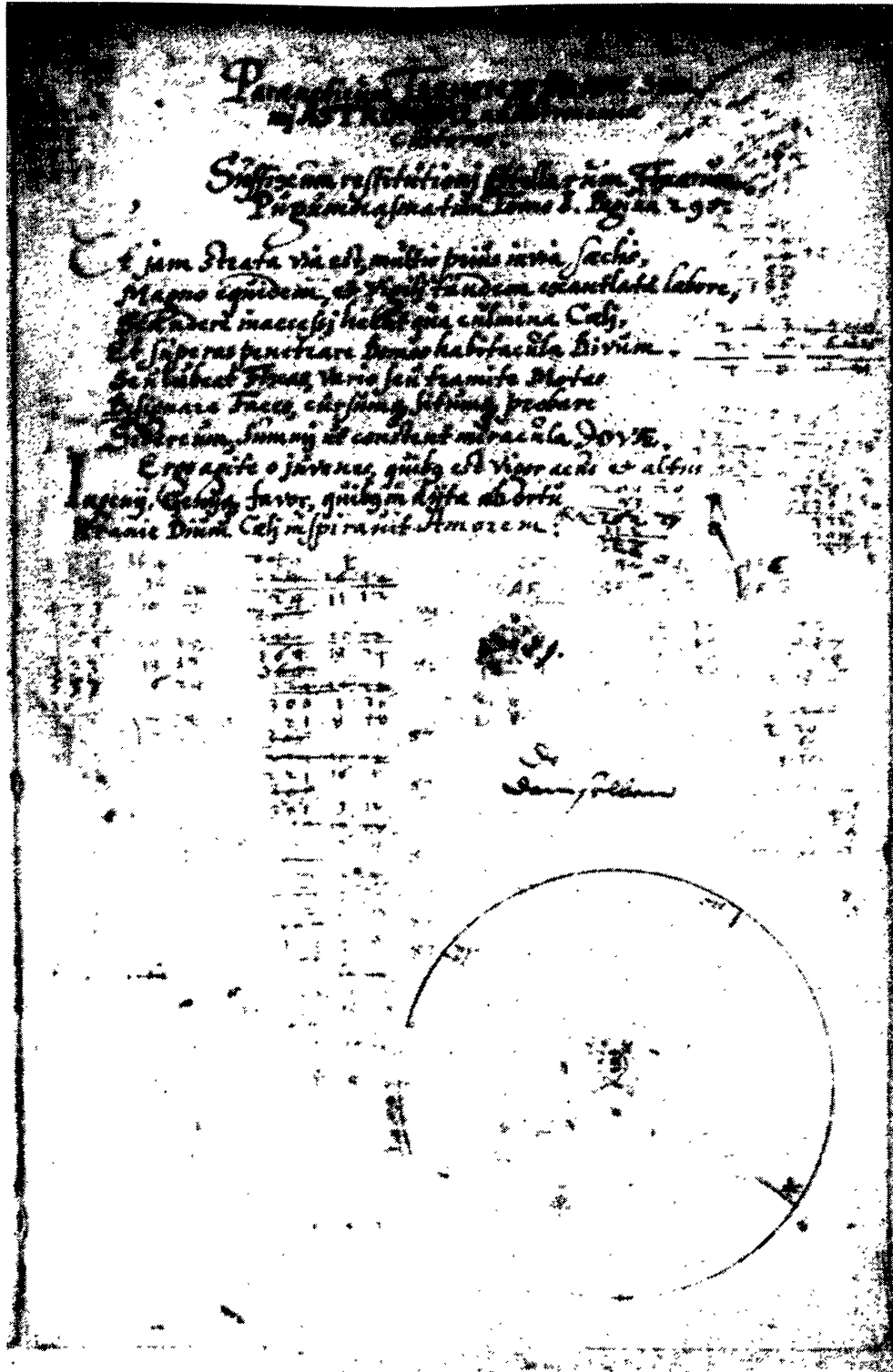


PLATE V. Kepler's manuscript for a proposed introductory leaf of a Mars ephemeris. Note the vicarious orbit near the bottom. After he abandoned this publication, Kepler used the page for other calculations. Archives of the Academy of Sciences of the USSR, Leningrad Kepler manuscripts, XIV, f. 372.

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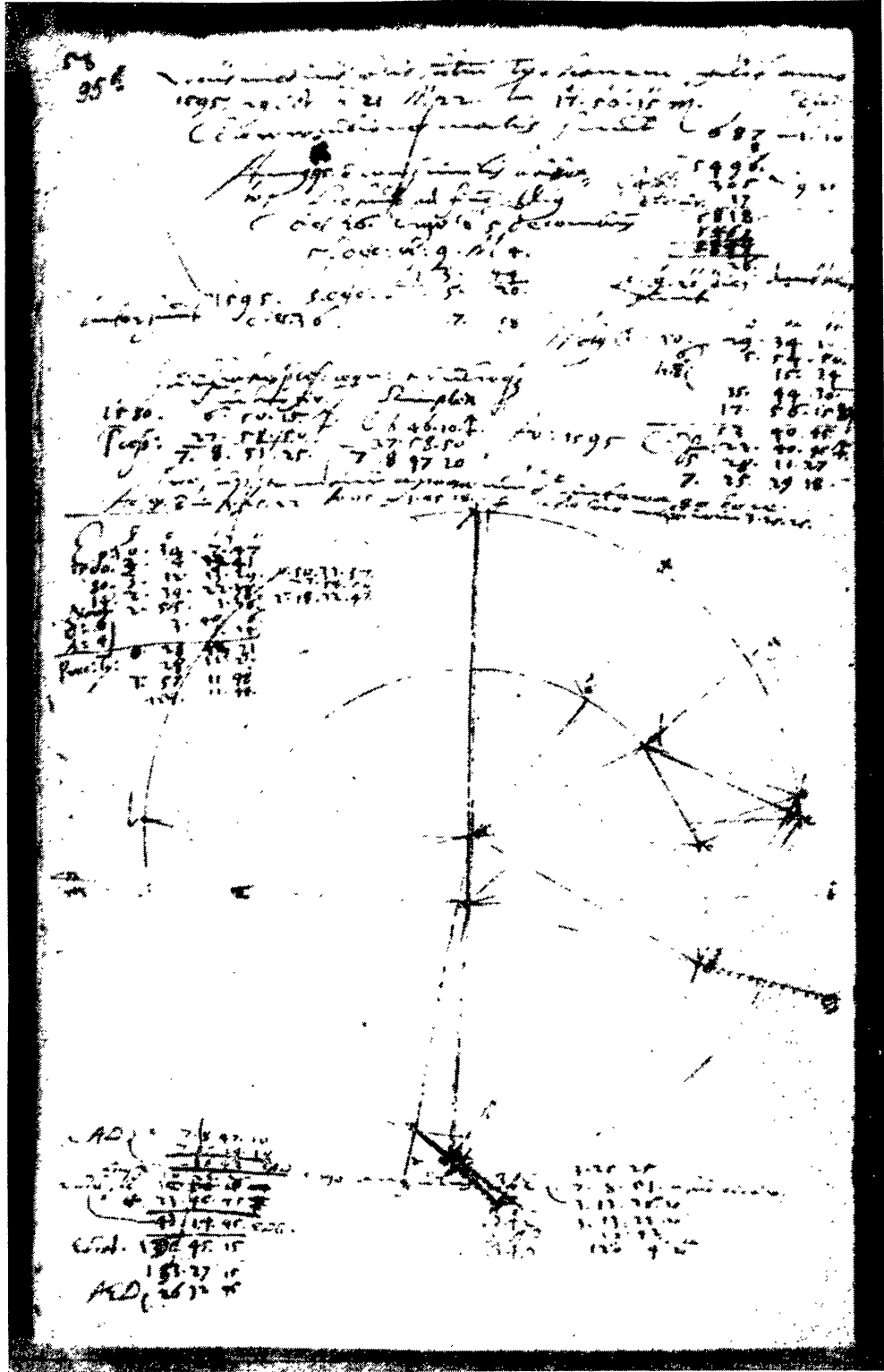


PLATE VI. Kepler's earliest Earth-Mars triangulation attempt, page 58 in his Mars workbook of 1600. Archives of the Academy of Sciences of the USSR, Leningrad Kepler manuscripts, XIV, f. 95v.

data, which Kepler believed were generally accurate to about 2'. In a celebrated passage, Kepler wrote: 'God's goodness has granted us such a diligent observer in Tycho Brahe that his observations convicted the Ptolemaic calculation of an error of 8' of arc. It is therefore right that we should with a grateful mind make use of this gift to find the true celestial motions' (6).

Fig. 3 (b) depicts the eccentric orbit with its equal-and-opposite equant. Because the angular motion is uniform about the equant, the opposite angles are equal, and the orbital motion at the aphelion is much less than at the perihelion. This was precisely the kind of motion that Kepler the astrophysicist desired: the planet's speed is inversely proportional to its distance from the Sun, a quite reasonable hypothesis if we assume that some physical emanation from the Sun is responsible for propelling the planet in its orbit. For Kepler this was a very fundamental idea; we can call it his *distance law*.

Although the outer planets had an equal-and-opposite equant in the Ptolemaic system, Kepler knew that the Sun–Earth orbit did not. In order for the Copernican system to be a real physical one, Kepler recognized that the same mechanism must apply for the Earth's orbit as for Mars<sup>1</sup>. The varying speed in longitude of the apparent Sun throughout the year required a certain definite spacing between the Sun and the point of uniform angular motion (traditionally taken as the centre of the orbital circle). The same spacing can be preserved, however, if we retain an equant but recentre the circle midway between the old centre and the position of the Sun. Such a model will predict virtually the same longitudinal motion, but with different Earth–Sun distances, and would, of course, provide a physical mechanism similar to that for Mars.

But how to find the varying distance of the Sun? One way would be to measure the apparent diameter of the Sun at different times throughout the year. And so let me digress here, just as Kepler did.

When Kepler arrived in Prague, he bet Longomontanus that he could solve the theory of Mars within a week. He lost the bet, of course—it actually took five years, but, as he apologized in the *Astronomia Nova*, he took one year out for optics. His resultant work, the *Astronomiae pars Optica*, lays the foundation for modern geometrical optics. In it he explains, for the first time, how an inverted image is formed on the retina of the eye, and he clearly defines the light ray. Also, he investigates the effects of apertures of various sizes and shapes on the formation of an image (7). Such considerations were of fundamental importance in observing the solar diameter, because the variations were rather small, but unfortunately the results were not conclusive.

Thus, Kepler turned his attention to another exceedingly ingenious way to locate the position of the Earth's orbit. He knew that Mars returned to the same point in space every 687 days, but that the Earth would be at two different points in its orbit since in that time it would not yet have completed its second full revolution. Kepler's manuscripts for the first two years of his work on Mars are apparently almost completely intact, and in Plate VI we see the very first time when Kepler tried such a triangulation. These results were ultimately very important, for they showed that his physical intuition was correct and that the Earth's orbit had to be moved to a new centre. Hence, it could have a physical mechanism and a distance law, just as did the other planets.

Kepler, in fact, already had rather definite ideas about the physical mechanism involved. Through Johannes Taisner's book on the magnet (1562) and, later, William Gilbert's, he convinced himself that the planetary driving force emanating from the Sun must be magnetic. He believed that both the Sun and the magnetic emanation were necessarily rotating in order to impart a continuous motion to the planets. From the distance law, he deduced that the strength of the emanation decreased in inverse proportion to distance, and he therefore concluded that the emanation spread out in a thin plane—unlike light, which filled space and decreased as  $1/r^2$ .

When he applied the distance law to the Earth's orbit, a difficult quadrature resulted that he could handle only by laborious numerical calculations. Then Kepler had the fortunate inspiration to replace the sums of the radius vectors required by the distance law with the areas 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, it provided an accurate approximation to the orbital motion predicted by the distance law. In Fig. 3 (b) it is easily seen that the equant theory represents the law of areas only if the equant is placed directly opposite the Sun and at an equal distance from the centre; the distance law and the law of areas are then rigorously equivalent at aphelion and perihelion.

At this point, Kepler had (1) an accurate but physically inadmissible scheme for calculating longitudes (the vicarious hypothesis), and (2) an intuitively satisfactory physical principle (the distance law) that was applicable to the Earth as well as to the other planets, but that left an unacceptable 8' error in predicting the heliocentric longitudes of Mars. In order to preserve simultaneously both his accurate longitude predictions and the properly centred circular orbit, Kepler next added a small epicycle to his circle. This was a time-honoured device, used not only by Ptolemy but by Copernicus and Brahe as well. The earliest pages of Kepler's Mars notebook from the first few weeks with Tycho Brahe in

Prague, show numerous experiments with epicycles. It is fascinating to see that although Kepler is here exploring very new ground, he can still adapt his tools from traditional astronomy. Nevertheless, he was distressed by having to introduce such an absurd device. He argued that just as sailors cannot know from the sea alone how much water they have traversed, since their route is not distinguished by any markers, so the mind of the planet will have no control over its motion in an imaginary epicycle except possibly by watching the apparent diameter of the Sun.

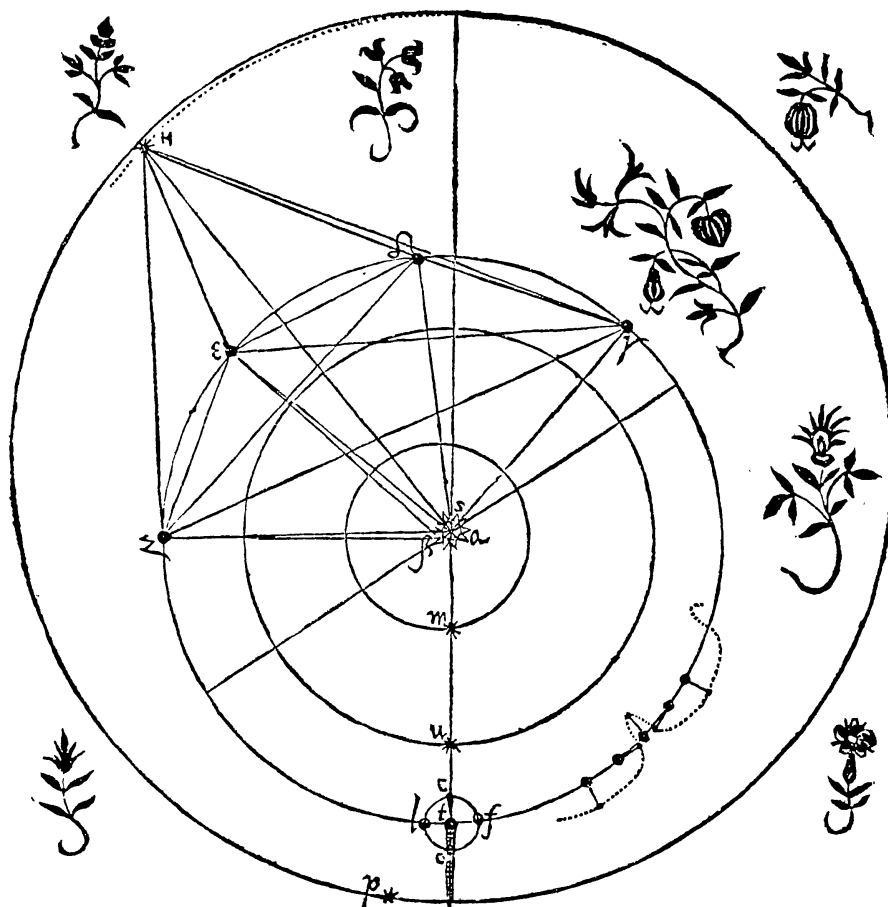


FIG. 4. The triangulation that revealed the non-circular orbit of Mars, from the *Astronomia Nova* (1609), chapter 27.

Kepler had difficulty in preserving the circular motion when he adopted an epicycle; it is therefore not surprising to find that our astronomer next turned to a closer examination of the shape of Mars' path. Having established the proper position of the Earth's orbit by triangulation of Mars, he was able to turn the procedure around and

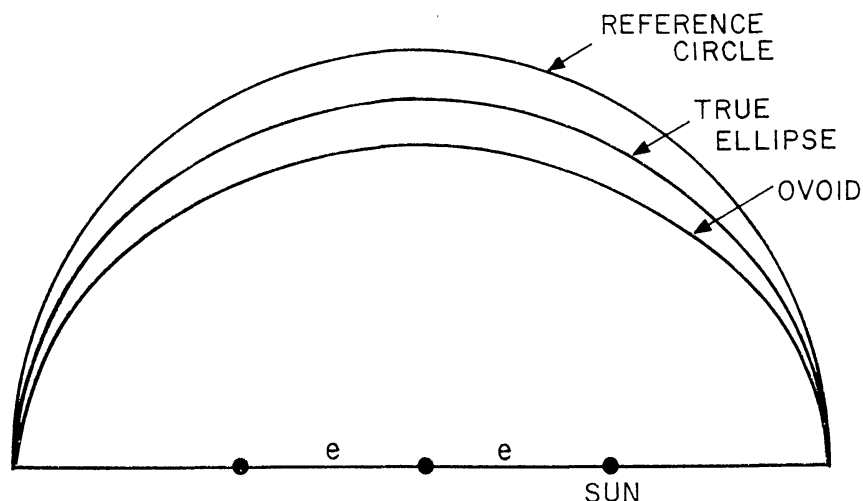


FIG. 5. Kepler's ovoid orbit compared with the final ellipse: the eccentricity is greatly exaggerated.

to investigate a few points in the orbit of Mars itself. The results are shown schematically in Fig. 4, taken from the *Astronomia Nova*. I say schematically because this method did not yield an exact quantitative position. Instead it showed only qualitatively that the orbit was non-circular. Kepler recognized that observational errors prevented him from getting precise distances to the orbit. Because of this scatter, he had to use, as he picturesquely described it, a method of 'votes and ballots'.

Armed with these results, Kepler found in the epicycle the convenient means for generating a simple non-circular path. The resultant curve is shown in Fig. 5. On this scale it differs imperceptibly from an ellipse, although actually the curve is slightly egg-shaped with the fat end toward the Sun.

Kepler required that the motion with the generating epicycle should satisfy his law of distances, which could be approximated by the law of areas; some details of the construction are found in the extended caption to Fig. 6. If Kepler had had access to the integral calculus, he would have found that the egg-shaped or ovoid curve has a very elementary equation, but this he did not know. We must remember that even the equals sign had been invented only in the preceding generation, and Descartes' analytic geometry was still in the coming generation.

In working with the ovoid, Kepler got himself into a very messy quadrature problem that could best be tackled with the help of an approximating ellipse. Most popular accounts of his warfare on Mars leave the reader puzzled as to why Kepler did not immediately abandon the ovoid and adopt the ellipse. As Fig. 6 demonstrates, the approxi-



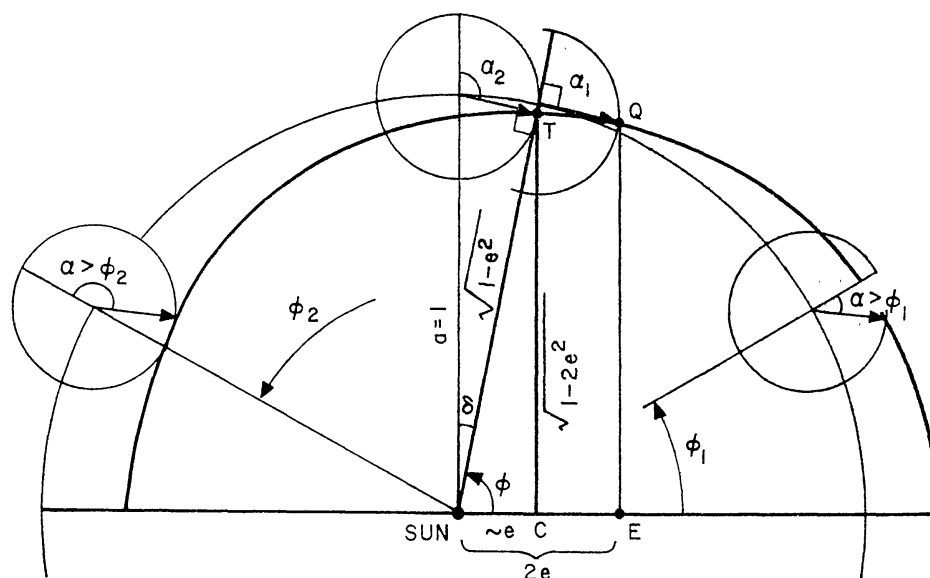


FIG. 6. The epicyclic construction of Kepler's ovoid (the darker curve). The epicycle has radius  $e$ . Angle  $\alpha$  moves uniformly with time, whereas  $\phi$  moves non-uniformly in order to satisfy the area law, so that  $\int \frac{v}{r^2} d\phi = ca$ . If this construction had an equant, it would fall  $2e$  from the Sun at  $E$ , and Mars would reach  $Q$  in a quarter period; hence,  $\alpha_1$  in the epicycle must be very close to  $90^\circ$ . As the epicycle centre moves through angle  $\delta$ , the epicycle vector will also advance by  $\delta$  since  $d\phi$  is very near its mean rate in this part of the orbit (so  $da \approx d\phi$ ). Thus,  $\alpha_2 = \alpha_1 + \delta$ , and the angle at  $T$  is a right angle. Then the line  $\text{SUN}-T = \sqrt{1-e^2}$  and  $TC = \sqrt{1-2e^2}$ . Since the semi-minor axis of an ellipse is  $a\sqrt{1-e^2}$ , the approximating ellipse to Kepler's ovoid has eccentricity  $\sqrt{2}e$ . Kepler called angle  $\delta$  the 'optical equation'. He finally realized that an ellipse of eccentricity of  $e$  gave the required path when he noticed that  $\secant \delta (= 1/\sqrt{1-e^2} = 1 + 1/2 e^2)$  exceeded unity by precisely the width of the lunula between the circle and the non-circular orbit. 'It was as if I had awakened from a sleep', wrote Kepler.

mating ellipse has an effective eccentricity of  $\sqrt{2}e$ , where  $e$  is the distance from the centre of the circle to the Sun. The diagrams show how inaccurately the triangulation method determined the points on the orbit of Mars. If these points had been well determined, Kepler would have seen immediately that the ovoid departed from the circular orbit by twice as much as it should have. His real hold on the problem came through the predicted longitudes, not the distances, and here again he found the  $8'$  discrepancy in the longitudes at the octants. Kepler wrote the previously quoted celebrated passage about the  $8'$  in connection with the errors of a circle, but it is quite possible that he first discovered it in examining the ovoid. The symmetry of the situation shows that if there is an  $8'$  error in a circular Ptolemaic orbit, there

ought also to be about an 8' error in the ovoid, which deviates equally on the other side of the correct ellipse.

Luckily, in the end Kepler abandoned the epicycle and adopted the ellipse that lay half-way between his ovoid and the circle. But the process was not simply the method of 'cut and try' so often imputed to Kepler by popular accounts. He was still seeking a single physical mechanism, to explain not merely the varying speed of Mars in its orbit, but also the varying distances. His answer came in an extension of the magnetic effects that propel the planets in their orbits. Kepler drew a very charming analogy to a boatman in an amusement park. Apparently, a cable was stretched across a stream and the small boat attached to the cable. The oarsman, by directing the rudder, could use the flow of the stream to propel the craft back and forth from one side to another.

From Gilbert's book, Kepler knew about the magnetic axis of the Earth. Such a magnetic axis, he proposed, could act as the rudder in the Sun's magnetic emanation, guiding the planet first near and then far from the Sun. If the magnetic axis is fixed in space, then its projection as seen from the Sun will be  $\cos \theta$ . Such a cosine term appears in the polar equation for the ellipse:

$$r = a(1 - e^2)/(1 + e \cos \theta) .$$

To the first order in eccentricity, the ellipse satisfies this physical picture of the magnetic axis governing the advance and retreat of the planet. For Kepler, who did not work with the polar equation, the real hurdle was to find the geometrical equivalents between the librating magnetic axis and the ellipse. 'I was almost driven to madness in considering and calculating this matter', he wrote. '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' (8).

Indeed, Kepler was luckier than he knew. Just as there is an approximating ellipse to the oval he originally tried, so there is an approximating oval indistinguishable (with Tycho's data) from this final ellipse, the so-called *via buccosa*. But when Kepler found that the ellipse satisfied the observations, he must have hastily assumed that no other curve would do; thus, driven by his persistent physical intuition, he had continued until he almost accidentally hit upon the right curve.

With justifiable pride he could call his book *The New Astronomy*; its subtitle emphasizes its repeated theme: 'Based on Causes, or Celestial Physics, Brought out by a Commentary on the Motion of the Planet

Mars'. Today, Kepler is primarily remembered for his laws of planetary motion. Although his magnetic forces have fallen by the wayside, his requirement for a celestial physics based on causes has deeply moulded science as we know it today. It was, in effect, the mechanization and the cleansing of the Copernican system, setting it into motion like clock-work and sweeping away the vestiges of Ptolemaic astronomy. The results can very appropriately be called the Keplerian system. In the preface to Kepler's long-awaited *Rudolphine Tables*, finally published in 1627, he felt compelled to excuse the extended delay. He says that 'the novelty of my discoveries and the unexpected transfer of the whole of astronomy from fictitious circles to natural causes were most profound to investigate, difficult to explain and difficult to calculate since mine was the first attempt' (9). Kepler's *Astronomia Nova* might have been forgotten had it not been for the brilliant success of the *Rudolphine Tables*, whose predictions were nearly two orders of magnitude more accurate than previous methods. Today, with the clarity of hindsight, we see not only that the *Astronomia Nova* was truly 'the new astronomy' but that Johannes Kepler himself deserves to be remembered as the first astrophysicist.

#### ACKNOWLEDGMENTS

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- (1) Kepler, J., 1596. *Mysterium Cosmographicum*. Reprinted in the standard Kepler edition (KGW, Munich, 1938–) *Johannes Kepler Gesammelte Werke*, I, 11.
- (2) Kepler to Maestlin, 3 October 1595; KGW, 13, 40.
- (3) Kepler, J., 1596. *Mysterium Cosmographicum*; KGW, I, 13.
- (4) Kepler, J., 1609. *Astronomia Nova*; KGW, 3, 109. It is scandalous that this work has never been published in English; the passage quoted is from an almost completed translation being prepared by Ann W. Brinkley and myself.
- (5) After Kepler's death in 1630, his manuscripts changed hands repeatedly—they were once owned by Hevelius and a list of them appears in the *Philosophical Transactions*, 9, 29–31, 1674—but they were finally bought by Catherine the Great for the Academy of Sciences in St Petersburg, and to this day they are preserved in Leningrad. I wish to thank Dr P.G. Kulikovskiy and Dr V.L. Chenakal for providing me with an excellent microfilm of Volume XIV, which

contains the principal papers relating to the analysis of Mars. The greater part of this volume comprises a notebook of nearly 600 pages, which represents virtually all the work for 1600 and 1601. There are several draft chapters for the *Astronomia Nova* and material for an ephemeris, from which Plate II has been selected. It was not until 1605 that he found the ellipse, and unfortunately no manuscripts remain from that part of the work.

- (6) Kepler, J., 1609. *Op. cit.*, 178.
- (7) 1971 was not only the 400th anniversary of Kepler, but also the 500th anniversary of Albrecht Dürer. It is interesting to note that Kepler knew Dürer's great book on art theory, the *Underwesung der Messung* (1525), which illustrates not only the Platonic solids, a construction for an erroneously egg-shaped ellipse, but also a device that uses threads to assist in drawing an object in perspective. Kepler employed a rather similar procedure of threads to investigate the formation of an image, and Stephen Straker, in a doctoral dissertation written at the University of Indiana, suggests that Kepler may have got the ideas from Dürer.
- (8) Kepler, J., 1609. *Op. cit.*, 366.
- (9) Kepler, J., 1627. *Tabulae Rudolphinae*; *KGW*, 10, 42-43.

#### JOHANNES KEPLER:

##### PREFACE TO THE RUDOLPHINE TABLES

Translated by *Owen Gingerich* and *William Walderman*

**Translators' note:** The *Rudolphine Tables*, published in 1627, constitutes Kepler's last major contribution to astronomy. The tall, slender volume is half filled with numerical tables, half with Latin explanations. His tables enabled the user to calculate with unprecedented accuracy solar, lunar and planetary positions for any date in the past or future. For Kepler, they were the proof of the pudding, the substantiation of his laws of planetary motion. He called them 'my chief astronomical work'.

Like most of his prefatory writing, the introduction to the *Rudolphine Tables* is a remarkable mixture of polemics and autobiography. Strangely enough, this fascinating statement of Kepler's most mature views on astronomy and astrology has never before been translated out of its original Latin. But his account speaks for itself, and there is no further need to introduce a preface.

The science of the stars includes two parts: the first concerns the motions of the stars, the second their effects in the sublunary domain. The ancients used to designate both by the same word, Astrology. But since there is an enormous difference between these two parts with respect to their certainty, later usage even distinguished them by name. Thus the doctrine on the motions was instead called Astronomy, because the laws of the motions are immutable and are established by the highest principles; the other part, filled with conjectures, has the once-common name of Astrology all to itself. Certainly it first arose in

the minds of men, who, wanting to foresee the future, undertook the contemplation of celestial affairs. Though man is the most outstanding work of the whole Universe, indeed, the lord of all nature and the image of God the Creator, yet his origins are feeble, ridiculous and an almost shameful drawing together of a little liquid and menstrual blood. This takes place in the vilest part of the mother's body; the food of the newborn babe is milk; its work is either sleeping or crying; its life is sordidness; its habits are trifles. And yet, from this workshop, as it were, men have come forth to us who lay out cities, who excavate ports, who destroy mountains, who span straits with bridges; princes, kings, monarchs. Likewise that celestial discipline, amenable to invention, had its origins in the mental image of the horrible solar and lunar eclipses, and from comets, whose apparitions were followed by the most dreadful catastrophes for the human race. Thus, starting out from these very slender and obscure beginnings of the formation of beliefs about the stars and the various constellation figures and of a desire to know the future, she first acquired a certain life force. Using this, she broke out from the recesses of thought into the light of open profession, and she began to be discussed openly among men. Then she was educated through dreams and the trifling matters of natal predictions, gradually grew to adolescence, and finally, abandoning her toys (so to speak) with mature boldness, she passed through traditional exercises of celestial meditation on to many useful applications in life, wonderful devices, and to the provision of necessities. Step by step she became increasingly prominent for the correction of morals and even for the knowledge of God the Creator himself.

However, just as years can be seen in the rings of trees, similarly, certain features from this origin appear in the whole composition of this most divine art, so that Astronomy, the daughter and nursling, cannot deny her mother and nurse, Astrology. The divisions of astronomy are: observations, hypotheses, mechanics, and calculations or tables. Each of these is used separately for predictions. The concern for foreseeing the future taught men to observe the stars; fear of floods of the Nile made men observe the rising of Sirius. Inventors established hypotheses in order to display openly the causes of the various observations. Not only could the annual harvest be predicted from the stars, but even the positions of the stars themselves could be predicted from the hypotheses. And so the signs of the future might be known earlier in the mind than in the Universe. For this use arithmetic supplied the calculations and the tables expressing the force of the hypotheses; and mechanics supplied the circles, theories, and dials; so that whenever the mind should succumb to fatigue, the hand would take over, laying open and smoothing the road which led straight to the present, past or future positions of the stars. From this knowledge, for example, the destinies of new-born children could be determined.



However, a more mature age of practice, with a more sublime and flawless goal, not only established, but strengthened and consolidated them all, superseding those parts of the art that came from an exceedingly obscure and foolish infancy. Today sidereal philosophy can no longer do without astronomical tables; he who would banish them from philosophy and the podia of professors would as well abolish the Sun from the Universe.

For, even if we say nothing about the necessities of daily life and about the principles of the arts that serve these, all of which are sought and then acquired and perfected from astronomy, nor speak of chronology, of the computation of feast days, of agriculture, of medicine, of geography, of navigation, let us consider metaphysics and theology themselves. If as all sects of philosophers profess, all theologians of all ages proclaim, all saints divinely inspired affirm, 'the heavens declare the glory of God, and the firmament showeth his handiwork' (Psalm 19), how do we perceive this more clearly, by our naked eyes, or by the elevation of our minds? We literate men have eyes in common with the uneducated; in fact, as men we have them in common with the beasts. Although all of us, both educated and uneducated, behold the wonderful variety and beauty of the stars together, we do not perceive with our naked eyes the ornate interior of the work, the order, constancy and eternity of the celestial revolutions. Here we need our minds, the memory of former observations and the comparison with present ones, and finally, the prediction of future positions, so that, if we represent whatever has been observed at any time by an established procedure, and if we see happen just what we have predicted, then we will confirm with the fullest belief the immutable nature of the Supreme Mover and the most provident governing of the Universe, matters which, I say, are not immediately obvious to the eyes and which are repeatedly called into doubt. He who would here snatch away from the learned the astronomical tables, an aid to memory, would blind human eyes, dull the observations of the stars and show man's knowledge to be of no worth. He would send the human race, which throughout the long succession of centuries has been instructed and educated by the greatest efforts of inventors on the highest matters, back to the cradles of its primitive ignorance.

But the same union of separate goals that gave astronomy her origin still persisted; in fact, it continued even when the art was perfected, and even now as the discipline passed through sublime stages, it retained a certain pleasant memory of its childhood, so that the study of divination, for which the tables were first written down, also led to their emendation throughout the passing centuries. One might see to some extent the image of its childhood in the *parapegmata* [astronomical computing tables] of the Greeks, or in the fixed celestial year of Dionysius,

not to mention its beginnings by the Chaldeans, now so obsolete on account of their antiquity that their tenuous fame scarcely lasted until our time. When Dionysius realized that the seasons of the year did not invariably return to their own day, either with the meanderings of the erratic nineteen-year period or even with the risings and settings of the fixed stars, he began to observe the five wanderers and to lend an ear to the Chaldeans, whom Greek astronomers began to know under the Seleucid kings. He began to relate the first and last visibilities of the wanderers as well as their achroynchal rising and settings to the appearance of the fixed stars and the Moon, and to record these observations in *parapegmata* of the previous years in order to remember them and to compare the subsequent changes of the weather. No tradition exists among the Greeks of more ancient records, and it seems never to have occurred to the Chaldeans themselves before they were conquered by the Macedonians that an exact prediction of the five planets could be included in astronomy, although they might have had an idea about that method by their clever recording of observations made with the aid of the configuration of fixed stars. For though they saw that the individual planets observed definite yearly orbits, nevertheless these laws governing the revolutions were joined together with as much liberty as the terms of the positions of the magistrates in some republics and the consulships among the Romans, where after a decade they used to be renewed again. From thus seems to have arisen the word, adopted by Cleomedes, *προαιρετική*, or 'arbitrary motion', which we call 'proper'. From this comes the idea of divinity in the planets, and their power over human affairs, and from that comes the distribution of magistracies, as it were, in Chaldean astrology: which planet should be lord of birth, lord of the year, lord of the ascendent? Which presides over each day, each hour? By how many votes does each win? All of these things imply freedom in the theory of the motions, and are therefore responsible for the failure in the exact determination of the planetary approaches to certain fixed stars.

Later Hipparchus accepted these Greek observations, both arranging and comparing them with the experience of his own time, and he edited a rudimentary sort of table from which the planets and their seasonal periods could be seen, and from which the times of their stationary points and retrogressions could be determined by a rather simple calculation. And so this can be considered as the adolescence of the tables.

Ptolemy was the first person who, after collecting together the aids of the ancients, especially Hipparchus, and also the motions of his own time, edited the whole work of the tables and thereby established by its length a sort of young maturity. Although in his *Almagest* he repeatedly brought forth ideas pertaining to the supreme philosophy, and expressly

brought the art of astronomy to perfection as it should be, nevertheless, besides his great work on the motions, he also produced one on the effects, the *Tetrabiblios*. He addresses both works to Syrus, and although he does not assign any place within his *Almagest* to the prediction of nativities, he treats it in the *Tetrabiblios*, a work in which one sees many trifles of the Chaldeans reduced in a certain artful form; thus, after that very futile infancy of conjectural astrology, it first begins under this master to learn its ABCs, so to speak.

Nevertheless, after the age of Ptolemy and his successors, philosophy fell on hard times, when Greece was enslaved to the Romans, and when not only her liberty, but also her former intellectual vigour were lost. Not only was correct reason publicly contaminated by superstitions but also freedom by servile suffering. But, indeed, those people who believed in Christ, dispersed throughout the whole world because they were scorned by the philosophers of that time, in turn considered astrology to be a pagan art because it was thoroughly polluted by superstitions, and to be soothsayings injurious to God; sometimes they dared to damn it so thoroughly that there were those who chose to desert Christianity itself rather than their profession. From other regions arose new nations and empires, first the Huns and Goths, and then the Arabs, of which the first two were stupid and barbarian, whereas the last were clever but most superstitious. The study of the stars, driven out of Europe by the former and sent down to the latter in Africa, served in a most disgraceful slavery, under astrologers, soothsayers, magicians, and fortune tellers who gave answers to anyone who asked as if from the tripod in the place of the oracles. These men, entangled by impiety, sought gains alone; therefore stellar observations, the accuracy of the tables, and their comparison with the sky were of no concern throughout several centuries.

Then, finally, in the ninth and tenth centuries after Christ, the Goths and the Franks gradually began to lose their barbarity as they established empires, and the Saracens began to lose their superstition as they expanded over a wide territory. Then the Europeans gradually began again to seek the full doctrine of divination; the Arabs, and likewise learned Jews, took pity on its imperfections and undertook the task of emendation. Thus, with the successive centuries, as the commerce of Frederick II of Swabia, Alfonso of Spain, and the Roman emperors increased with the Saracens in Palestine, Sicily, Italy, and Spain, it finally came about that the practice and care of this art passed over to western Christians. Not only were many astrological books translated from Arabic into Latin, but even the *magnum opus* of Ptolemy, which the Arabs were accustomed to call *Almagest*, from *το μεγαιστον*. Although the clearly royal concern of Alfonso soon shone forth, com-

mending him to all posterity by his commissioning of the tables that we call Alfonsine; nevertheless, that king himself in a preface at the beginning of several copies began his discourse with the connection of sublunary matters to the motion of the stars, and displays many presumptions about the art of calculating nativities. And so Astronomy, even though an adult, has not forgotten her milk and cannot go without it.

An age auspicious for scholarship received the tables constructed under Alfonso, an age in which many new academies were established throughout Europe from the small number of older ones. This age now constituted a kind of manhood of Astronomy; superstitions were more and more cleansed away from the knowledge of the most important things, and the discipline was called back to its highest goal, and to its usefulness in everyday life to Geography and Navigation, which art opened a new world, joining the east to the west from the far side, and bringing almost all of it together under one empire. Added to this was the internal concern of religion for the correction of the Easter holiday, whose aberrations were made more evident by the propagation of this study. Therefore the Germans assiduously applied themselves to developing this study especially, in the schools of Vienna and Prague. Schindel, Peurbach, and Regiomontanus quickly discovered what was good in the Alfonsine Tables, and also that the reliability of the tables was less than their reputation. And therefore, these men themselves and their disciples throughout Germany and Italy, such as Walther of Nuremberg and Domenico Maria of Bologna, worked hard at observing the stars more diligently, and recorded them, either for their own use or for that of posterity. They also brought to light the ancient memoirs of Ptolemy, Al-Battani, Jabir ibn Aflah, and Alfonso, adding helpful explanations, amending them, and preparing all parts of spherical astronomy with new subsidiary tables for the easier use of this knowledge. And although Regiomontanus, who would have been equal to the task on account of his genius, died a premature death, he was succeeded in the concern for these corrections by Nicolas Copernicus, a canon of Varmia in Prussia, a pupil of Domenico Maria, a man of the highest genius, and (what is of great importance in these matters) a free spirit. His work on the revolutions of the planets, including the correction of the tables, was prepared in a new form with the greatest labour; although he kept it in his desk for twenty-seven years, nevertheless, at the very end of his life he handed it over to the Nurembergers to publish.

Although this work contains tables in addition to the explanations of demonstrations, there is, however, no one today, so far as I know, who uses them for calculations. He was succeeded within a few years by Erasmus Reinhold, a man most knowledgeable in every sort of disci-



pline, and especially and naturally suited for mathematics because of his admirable perspicuity and facility in abstruse matters. Reinhold undertook the task of finishing the tables of Copernicus, who was already dead; he named them the Prutenic Tables, either from Copernicus the Prussian, or from his Maecenas, the Duke of Prussia, and he drew them up for a chosen meridian. The Königsberg on which the epochs of the Prutenic Tables are based is not the one in eastern Franconia, which was the home of Regiomontanus, but a different town, in the duchy of Prussia on the shore of the Baltic Sea.

The reasons why Reinhold undertook this work may be found in the work itself; but he certainly seems to hide two of them. For the tables ought to be handy canons, easy to use; the authors of the Alphonsine and other tables have aided this handy use even by the form of their books, the numerical tables being bound together and very short instructions being placed at the beginning. The book of Copernicus, on the other hand, has the tables dispersed throughout the text among the demonstrations in the manner of the Ptolemy's *Syntaxis* [*Almagest*]. Thus it happens that the mind of anyone desiring to use the tables is distracted by the text, and the work deprives itself of its own chief usefulness. Secondly, Copernicus insisted on 'absurd' hypotheses, which Reinhold believed would have offended and frightened off the readers. He therefore decided that he should leave out any mention of the strange suppositions as well as the copious and tedious demonstrations, and publish the tables themselves separately in the form of a handbook, after correcting and calculating them more diligently, so that they might represent more exactly the fundamental observations on which Copernicus built his structure.

With this in mind Reinhold undertook the work, and he shows that he wore himself out in this huge and disagreeable task. If you wish to know his purpose, it is very laudable indeed: the definite knowledge of the motions, the length and starting point of the year, the equinoxes, solstices, eclipses, and the great conjunctions, so that from the most sublime collection of these things, the wisdom and goodness of the Creator might shine forth. But, at the same time the author does not hide the study of predictions, and shows what he attributes to the art of calculating nativities using few, but pregnant, words. He affirms that 'Events in this lower nature are affected or signified by the motions and position of the stars, and therefore can be predicted'. What more can be said? Thus on second thoughts the mother becomes more correctly the grandmother, and the daughter becomes the mother, since a granddaughter bearing the appearance of her grandmother is born, another Astrology. And so (as I have already written on this matter), the foolish daughter Astrology, by a business not universally approved, nourishes and sustains her most intelligent but impoverished mother,



Astronomy. And the author seems to confirm this very thing under the guise of denying it. For while he denies that he placed divinations before the erudite and useful work in the tables, he shows himself versed in this kind of exercise, and confesses that he gave it the second place.

However, lest anyone think that what has been written above shows that I consider a most erudite man to be classed among those superstitious Arabs whose sole concern was profit rather than philosophy, I encourage the readers to read Reinhold's preface to the *Theorica* of Peurbach, which he wrote in 1542 in a most pure and agreeable sort of style. From these the reader plucks the flowers of his mind—admirable in scent, exuding their fragrance from the innermost gardens of philosophy. Although one may deny that *events* of human affairs depend on the stars, nevertheless he is certainly forced to recognize some *effects* on human affairs. See page 178, and also page 197 of that commentary on Peurbach.

But let our discussion return to the point from which it has digressed, and let it even assign now maturity and an age of responsibility to Astronomy, which has been brought back among men. For what Reinhold claimed about the Alfonsine Tables, namely, that they do not agree with the phenomena precisely enough, many men most practised in observations have complained about also in the Prutenics, and this very year, 1625, offered a most evident proof. For example, throughout the whole year Mars has been observed much farther advanced in the sky than the Prutenic calculations predicted, and the error has grown through the months of August, September, and October, to the magnitude of four, and almost five, degrees. For Reinhold, in that he followed conjectures based on little data since no one had written out sufficient observations, thought that the revision should be in the mean motions, whilst the tables of prosthaphaereses [corrections] for equant and eccentricity would serve usefully both backward and forward for the entire duration of the Universe; he was deceived on both accounts, and indeed is caught by this very example. For in the mean motion of Mars, only the smallest quantity had to be changed, and actually the whole error of this year arose from the faults of the Prutenic prosthaphaereses.

Thus it happened that such aberrations were first discovered in the Prutenic Tables in the very region where the tables were edited, by learned men skilled in the observation of the stars, foremost among whom must be mentioned, for his great merit, Wilhelm, the most illustrious prince of the Hessians. Finally Tycho Brahe arose, a man outstanding in the nobility of the kingdom of Denmark, who, scorning the other studies of his peers and taking up the restoration of astronomy with his immense intellect, chose for himself this sole work in which he

passed his life and on which he spent the splendid family fortunes with which he was endowed. And this he did with a mind devoid of all astrological superstitions, concentrating upon the one and only supreme goal of all philosophy, the knowledge both of God and of himself. I consider this to be the most important part of his glory. He repeated this with unflinching regularity not only in his writings and poetry, in which he delighted, but as an incontestable witness also in his daily conversations: indeed, used to deride and detest the vanity, laziness, knavery, and filthiness of most astrologers, but in such a way that he by no means denied the effects of the stars on sublunary matters as a most important part of philosophy, for he knew how to distinguish with most accurate judgment the general *effects* of the stars from the *events* themselves in individual human matters. The common crowd, gullible for miraculous predictions, prompt to spread false rumours, and very wrong in both since they did not understand, sometimes opposed this very innocent man with an inept study of his reputation, with malicious talk, and with jealousy of his greatness.

He was accordingly an outstanding man: the proposer of the Rudolphine Tables; the recorder of a thousand fixed stars; the investigator of the motions of the Sun and the Moon; the observer of all the planets for thirty-eight years (and continuously for the last twenty), and he excelled all human expectation in diligence, observation, patience, and reliability.

I prefer that the reader learn from the *Astronomia Danica* of Christian Severinus Longomontanus rather than from my account what Tycho showed for the motions of the rest of the individual planets, besides what has indeed already been said. For he lived with Tycho continuously for ten years; I did so for scarcely a few months of his last two years. I came to Tycho at the Benatky Castle when Longomontanus was there only in February of 1600, after I was called from Styria by frequent letters from Tycho, the occasion being supplied by the publication of my *Mysterium Cosmographicum*. After coming to an agreement with him, I returned to Styria in June to fetch my family and my bookcases. In October of the same year, when Longomontanus had already left, I set myself up with my family at Prague, to be with Tycho. This proved futile, for a quartan fever had seized me on the trip, and it gripped me until the summer solstice of the following year; nor did it leave until I had returned to Graz on account of my legacy. When I went back to Prague in September, I was able to enjoy no more than two months of conversation with Tycho, since death carried him off on the 24th (new style) of the next November.

Therefore, Longomontanus indicates most accurately which parts of the Rudolphine Tables Tycho had finished while he was alive, what aids

or instructions he left, and what remained to be finished. He uses autograph corrections of Tycho for all the planets, and has applied them as a foundation in computing his tables. However, somewhere in my *Commentaries on Mars*, I, too, have indicated this, and a letter of mine on this subject written in 1601 to Giovanni Antonio Magini, Professor of Mathematics at the Gymnasium of Padua, which he had printed without my knowledge at Bologna in his *Supplement to the Ephemerides* twelve years ago, is extant, and this work of his, together with my letter, was reprinted in 1614 at Frankfurt.

Moreover, when, eight years after the death of Tycho, I published my aforementioned *Commentaries on the Motions of the Planet Mars* (in a way a part of the work on the Tables left behind by Tycho Brahe and something first begun at Benatky), Magini, impatient with the delays, used the foundations laid by me in that work and computed the tables of the prosthaphaereses of Mars, but in the usual form, and he made them a part of his supplement; he further obtained the tables of the motions of the Sun and the Moon from Vol. I of the *Progymnasmata*. Tycho Brahe had indeed computed the catalogue of a thousand fixed stars before he came to Bohemia, and had sent manuscript copies to libraries of kings and princes everywhere. I myself was the bearer of one sent to Vienna, when, in 1600, leaving Benatky in Bohemia and heading for Styria, I passed through Vienna. I therefore believe that Johann Gruenperger, S.J., has derived these thousand fixed stars for his Roman publication on the fixed stars from one of these copies; for the figures agree. Longomontanus has inserted the same thousand fixed stars into his *Astronomia Danica*, although they differ by one minute in longitude.

Thus, for a long time now everyone has been adding to his own boat the tables taken from the shipwreck of Brahaean astronomy, and the testimony of many students of astronomy agrees as to which parts of these tables genuinely belong to Tycho Brahe, and which in turn either belong to me, or for which I have introduced a new form. Wherever I could, I have chosen the reliable fundamental observations of the present day from Brahe alone, but I have sometimes adopted them from others and myself, either for the sake of agreement, or because Tycho's observations did not suffice for days suitable to me.

But on each of these points, something has been said in the introduction to my *Ephemerides*, and there will be a place to say more elsewhere. Handy tables ought to lack the weight that extensive comments would add to them. In the meantime the reader has the theoretical parts of the *Epitome of Copernican Astronomy*, which I published in 1621. In that book he will find both the forms of the particular hypotheses (for the general form, as I showed in the *Commentaries on Mars*, is common to

Ptolemy and Copernicus and Tycho) and the method of computing from them all the individual parts of these tables.

Before I end here, I feel obliged to excuse the very long delay in the publication of these tables, in fact, a lapse of twenty-four years since the death of Tycho Brahe. During all this time I have been earning an official salary from three emperors of Austria, and also in recent years there was added to this an annual salary from the exalted Archduchy of Upper Austria. In truth, if the time lost until now cannot be attributed to anything else except the passing of time itself and the present work, let us rather preserve what is at hand and leave what has passed as a criticism. However, to recall the difficulties created by obstacles at court, especially due to the intervention of wars, is unnecessary for those who know, and difficult to explain to those who do not. Moreover, these difficulties having been overcome, I have in the meantime followed with persistent thinking, which opportunity overflowed from the delays interposed in the exertion of thinking into the perfecting of celestial philosophy: my books, which in the meantime were published for public use, as well as the very method of the philosophizing, the novelty of my discoveries, and the unexpected transfer of the whole of astronomy from artificial circles to natural causes that were most profound to investigate, difficult to explain and difficult to calculate, my attempt being the first, all speak for me. These things, I say, and similar ones will render a quite sufficient account of the time to intelligent men.

But perhaps this aforementioned delay in bringing forth the natural causes of the motions will seem to some completely superfluous, worthless and even annoying. I have already opposed these thoughts with other relevant considerations, both in the Introduction to my *Ephemerides*, where I reply to David Fabricus, and in my *Epitome of Copernican Astronomy*, on page 5, in the chapter on the causes of the hypotheses, on page 334, in the preface to Book IV, and on page 622. Although actually that defence alone could suffice for me, I have made a not unhappy attempt to demonstrate for all of the planets an idea that Tycho Brahe first conceived and announced publicly in forming his lunar theory, namely, 'the causes of motions seem to be physical'; whoever rejects solid spheres cannot have it otherwise. I have shown that this applies to the calculations, and in this way according to my powers of comprehension I have both asserted and corroborated the suppositions and pronouncements of my master, the first author of the Rudolphine Tables.

But there will still be those who, disdainful of these remarks, will press me on the authority of the astronomer and philosopher Reinhold, whom I praised above, and who in his commentary on Peurbach said that he 'did not consider enforced physical debates, as others have done', and



who asks, 'What is more absurd than to disturb and confuse the geometrical inventions by the conjectures of the physicist?' Does he not dispute with Ptolemy, with Aristotle, and even with himself? In the latter preface to the *Theorica*, he writes: 'Perhaps these seven lucid bodies, even without spheres', which the art, or rather, the imbecility of our intellect has tried to justify for itself, 'have that force in them divinely, so that each preserves its own law and perpetual harmony in its own particular variety and irregularity of motions. For us, however, without all these spheres it would have been very difficult to understand and pursue intellectually at least the rationality, or as I say, the harmony of irregularity'. By these words he does not refute, but tacitly invites him who introduces natural forms and mechanisms of motions, and such forces similar to that of the magnet, which are not only more rational than all those very vast spheres, but they even offer to the mind both easy connections and a guide to calculations more expeditious for the apparent irregularities of the motions than the large spheres themselves. And so, I have tried to do that, following the advice even of Ptolemy himself (lest anyone think that I lack authority from the ancients), who demands 'making the hypotheses as simple and probable as possible'.

Therefore, it is easy for the man who has read Cremona and the other commentators on the spheres to judge how relevant it is that Reinhold excuses himself concerning the omission of physical discussions. These authors have made the spheres introduced from astronomy a great part of physics and metaphysics, as if the matter were explored completely, and by means of many arguments with contradictory opinions taken from everywhere, they have brought about a useless and infinite chaos of ridiculous questions. There was no care taken to direct those debates either for the instruction or ease of calculation, or to make clear to everyone through their reasonings the things that appear in the heavens. These reasons stood by themselves, in spite of their breakdown in these useless disputations, or even when the maker doubted the reality of the spheres in the Universe, as Reinhold did according to his own confession, and as Ptolemy himself repeatedly and with obvious approval does in his own case in the *Almagest*. Undoubtedly, for Reinhold this is 'to disturb and confuse by the illusions of conjectures the geometrical inventions, which have their own demonstrations'. In this manner, it could happen to me that an impudent person vainly boasting of his skill might deny the truth of these tables without considering the rationale of the celestial phenomena that they represent, and he might suppose them to be refuted if he has tried to demonstrate that the physical principles of which I boast are false. However, although I hope I shall defend the principles on which my work is based before other judges, I consider it enough for this profession if I have placed before the eyes



of the calculator the necessary definitions and precepts more clearly through these principles than through solid spheres. And with that excuse I now think that I have sufficiently defended the change from solid spheres to physical causes of the motions and have spoken enough of the reasons for so many delays. And so returning to the matter at hand, 'done fast enough if done well enough'; I thank immortal God with the highest praise who has prolonged for me the fluctuating course of my mortality up to this very day, when I put my hand for the last time to this work designed for his praise and for human use, triumphing over all difficulties with his gracious aid.

[Added in press by Kepler as a marginal note:] And yet two additional years in which the work, finished for a long time, was awaiting publication; besides other calamities that shook the province where I had fixed my residence with continued attacks, the work was at last even completely disrupted and ruined by a peasant's war, an Iliad of evils, so that it was resumed by me with new support, plans, and directions.

And the observations of the present, especially those of Brahe, will testify to the certainty of the calculations; about the future times we cannot presume more than either the observations of the ancients, which I have used, or the actual state of mean motions (not yet completely explored) and the agreement of physical causes, can show. Though the observations of Regiomontanus and Walther show that we must certainly consider the secular equations, so that I might record what has been demonstrated at this time in a single book, what sort and how large these equations are cannot be defined by the human race before the passage of many centuries, and the observations of those as yet unborn. (See how beautifully Willebrord Snell has commented on this thought near the end of the observations of the Landgrave, and of some of Tycho's.) And you have, *infra*, on the doctrine of eclipses clear evidence even from the observations of this time that the motions of the Sun, the Moon, and the *primum mobile* [precession] are not up to mathematical precision, but have rather slight physical increases and decreases in an irregular way.

And finally, whoever makes use of these tables in their works—students of astronomy, philosophers, and even present or future theologians—let them remember to attribute it for posterity entirely to the munificence of my patrons. Thus let it lift not only myself to the highest praise, but also Austria, its ruling family, which arose from that original possession whence the name had its origin to the domination of the whole Earth, as God guided its successes, and then the three emperors from that most august house: Rudolph II, who called Tycho Brahe to his court when he transferred from his native Denmark into Germany under most splendid conditions worthy of his illustrious origin, who gave me to him as an assistant while he lived and as a

successor in part of the work when he died, who received and approved the naming of the 'Rudolphines' proposed by Brahe, and who while living promised me sums sufficient for the publication; and next, Matthias I, who took on himself from his brother, along with the provinces, kingdoms and the Roman empire, also a concern for the arts and my salary; and finally Ferdinand II, who, besides everything else, gave the promised sums and with new liberality, even increasing them, and who ordered that the tables be published; so that, I say, they all merit thanks; and thus may the reader pray for the whole august house.

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