The Astronomy and Cosmology of Copernicus

It was close to the northernmost coast of Europe, in the city of Toruń, that the King of Poland and the Teutonic Knights signed and sealed the Peace of 1466, which made West Prussia part of Polish territory. And it was in that city, just seven years later and precisely 500 years ago, in 1473, that Nicholas Copernicus was born. We know relatively few biographical facts about Copernicus and virtually nothing of his childhood. He grew up far from the centers of Renaissance innovation, in a world still largely dominated by medieval patterns of thought. But Copernicus and his contemporaries lived in an age of exploration and of change, and in their lifetimes they put together a renewed picture of astronomy and geography, of mathematics and perspective, of anatomy, and of theology.[1]

When Copernicus was ten years old, his father died, but fortunately his maternal uncle stepped into the breach. Uncle Lucas Watzenrode was then pursuing a successful career in ecclesiastical politics, and in 1489 he became Bishop of Varmia. Thus Uncle Lucas could easily send Copernicus and his younger brother to the old and distinguished University of Cracow. The Collegium Maius was then richly and unusually endowed with specialists in mathematics and astronomy; Hartmann Schedel, in his *Nuremberg Chronicle* of 1493, remarked that "Next to St. Anne's church stands a university, which boasts many

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eminent and learned men, and where numerous arts are taught; the study of astronomy stands highest there. In all Germany there is no university more renowned in this, as I know from many reports." At the university the young Nicholas embraced the study of astronomy with a passion found only in the most exceptional of undergraduates. There he learned about the works of Sacrobosco, Regiomontanus, Ptolemy, and Euclid.

After leaving the Collegium Maius, Copernicus journeyed to the great university cities of Bologna, where he studied canon law, and Padua, where he studied medicine. Italy, then as now, bore the visible imprint of ancient Rome. It had become the recent home of Greek scholars, refugees from Byzantium, and in Italy Copernicus seized the opportunity to learn Greek. Italy was then in the high Renaissance, with Leonardo, Michelangelo, and Raphael creating their great masterpieces. But Copernicus, like many before him, had been drawn to Italy not for art but in search of a degree, and before he went home, he picked up a doctorate in canon law at the University of Ferrara. He thus became a lawyer by profession, with astronomy remaining an avid avocation.

In 1503, the 30-year-old Copernicus returned to Poland to take up a lifetime post as a canon of the Cathedral of Frombork, an appointment arranged through the benevolent nepotism of his uncle Lucas. Bishop Lucas was the head of the local government in Varmia, and the sixteen canons of the Cathedral Chapter constituted the next highest level of administration. In this northernmost diocese of Poland, Copernicus led an active and fruitful life for 40 years.

It was here that Copernicus served as an administrator of the Cathedral estates, collecting rents, resettling peasants, and writing an essay on currency reform. He served for a while as private secretary, personal physician, and diplomatic envoy for his uncle. And here in northern Poland, imbued with the spirit of Italian humanism, he made a Latin translation of a Greek work by Theophylactus Simocatta, a seventh-century Byzantine epistolographer, and perhaps he even painted his own self-portrait. Each of the Cathedral canons received an ample income derived from the peasants working the farmlands administered by the Chapter, and with such a tenured position Copernicus had the financial security to pursue his sideline of astronomical researches.

It was in Frombork that he wrote "For a long time I reflected on the confusion in the astronomical traditions concerning the derivation of the motion of the spheres of the Universe. I began to be annoyed that the philosophers had discovered no sure scheme for the movements of the machinery of the world, created for our sake by the best and most systematic Artist of all. Therefore, I began to consider the mobility of the Earth and even though the idea seemed absurd, nevertheless I knew that others before me had been granted the freedom to imagine any circles whatsoever for explaining the heavenly phenomena."

We do not know precisely when Copernicus began to meditate on the mobility of the Earth. He first announced his assumptions in an anonymous tract, today called the *Commentariolus*, that is, the Little Commentary. The *Commentariolus* was written before 1514, because in that year Matthew of Miechow, a Cracow University professor, cataloged his books and noted that he had "a manuscript of six leaves expounding the theory that the Earth moves while the Sun stands still." This brief document represents a first account of planetary motion, which was considerably extended and elaborated by Copernicus in later years. We do not know if the *Commentariolus* was widely distributed. In any event, it dropped completely out of sight until around 1880, when an example was found in Vienna and another in Stockholm. More recently a third copy has been found in Aberdeen, Scotland.

In Copernicus's day the sciences, and astronomy not least, were beginning to respond to the new opportunities offered by the printing press. It is interesting to notice that his lifetime of astronomical studies was to a large part made possible by his access to printed sources. During the Thirty Years' War, the Frombork Cathedral library was carried off to Sweden, and as a result most of his books are now found in the Uppsala University library. They include the beautiful Ptolemaic atlas printed in Ulm in 1486, Argellata's book on surgery, two editions of Pliny the Younger, plus works by Cicero, Herodotus, Hesiod, and Plato.

One of the earliest books he bought, presumably while he was still a student at the Collegium Maius, was the 1492 edition of the *Alfonsine Tables*. His personal copy is still preserved in its Cracow binding. These tables, originally constructed in 1273, represented the state of the art when Copernicus was a young man. They enabled him to calculate solar, lunar, and planetary positions for any date according to the Ptolemaic theory. Among the other scientific volumes remaining from Copernicus's personal library is the beautiful first edition of Euclid's *Elements*, printed by Ratdolt in 1483, and Stoeffler's *Calendarium Romanum magnum* of 1518. The annotations in this latter book show that Copernicus witnessed celestial phenomena on numerous occasions not mentioned in his published work.

A book that must have been enormously important during Copernicus's formative years was the Regiomontanus *Epitome of Ptolemy's Almagest*. His personal copy of this book is lost, but perhaps it is still waiting to be recognized by some sharp-eyed scholar. Our astronomer's principal access to the Ptolemaic theory must have come at first through the *Epitome*. It was not until after he had written the *Commentariolus* that the full text of Ptolemy's *Almagest* became available, in the edition printed in Venice in 1515. Copernicus studied the work carefully, as the manuscript notes and diagrams in the margins clearly show. Through this work he must have become more fully aware of the tremendous task facing any astronomer with the courage to construct a complete celestial mechanism.

During the 1520s, Copernicus worked extensively to elaborate his ideas, especially the planetary theory, if we are to judge by the scattered planetary observations recorded in his work. The *Commentariolus* had already hinted at a larger work, which Copernicus composed and continually revised during these years. By heroic good fortune, which we could scarcely have expected, his original manuscript has survived all these years. Perhaps the most priceless artifact of the entire scientific renaissance, it is now preserved in the Jagiellonian Library of Cracow University. The skilled draftsmanship, the precise hand, and, above all, the way in which he has elegantly written his text around the famous diagram of the heliocentric system (see Figure 1) convey the impression that this was a piece of calligraphy for its own sake, not a manuscript to be destroyed in the printing office, but an opus destined for the library shelf in the quiet cloisters of Frombork.

It is quite possible that his manuscript would have gathered dust, unpublished and virtually unknown, had it not been for the intervention of a young professor of astronomy from Wittenberg, Georg Joachim Rheticus. Exactly how Rheticus heard about Copernicus's work is still a mystery, although he may have seen a copy of the *Commentariolus*. In any event, he decided that only a personal visit to the source would satisfy his curiousity about the new heliocentric cosmology. Thus, in 1539, the 25-year-old Rheticus set out to that "most remote corner of the Earth," as Copernicus himself described it. Although he came from the central bastion of Lutheranism, the Catholic Copernicus received him with courage and cordiality.

Swept along by the enthusiasm of his young disciple, Copernicus allowed him to publish a first printed report about the heliocentric

FIGURE 1. *Autograph manuscript of Copernicus's* De revolutionibus, *fol. 9v, showing the heliocentric system. Photograph by Charles Eames, courtesy of the Jagiellonian Library, Cracow.*

system. In a particularly beautiful passage of the *Narratio prima*, Rheticus wrote:

> With regard to the apparent motions of the Sun and Moon, it is perhaps possible to deny what is said about the motion of the Earth. . . . But if anyone desires to look either to the order and harmony of the system of the spheres, or to ease and elegance and a complete explanation of the causes of the phenomena, by no other hypotheses will he demonstrate more neatly and correctly the apparent motions of the remaining planets. For all these phenomena appear to be linked most nobly together, as by a golden chain; and each of the planets, by its position and order and very inequality of its motion, bears witness that the Earth moves.

Rheticus had not come to Polish Prussia empty-handed. He brought with him three volumes, the latest in scientific publishing, each handsomely bound in stamped pigskin. These he inscribed and presented to his distinguished teacher. Included were Greek texts of Euclid and Ptolemy, as well as three books published by Johannes Petreius, the leading printer of Nuremberg. By the time Rheticus returned to Wittenberg in September of 1541, he had persuaded Copernicus to send along a copy of his work, destined for Petreius's printing office.

Tantalizingly little information survives concerning the actual publishing of Copernicus's book. We do not know the time required for the printing, the size of the edition, the methods of distribution, or the price. A few things can be conjectured from the standard practices of the day. Thus we can deduce that if a single press was used for the folio sheets, the printing of the 404-page treatise would have taken about four months. It is likely that the type would have been redistributed and continually reused, so that a competent technical proofreader would have been required on the scene.

Wildly diverse guesses about the size of the first edition have appeared in the literature. At the present time, I have located approximately 200 copies; perhaps an additional hundred exist that I have not found, and I would appreciate help in locating other copies. These numbers suggest an edition of at least 400, and perhaps 500. If many more were sold, it seems improbable that a second edition of about the same size would have been required 23 years later. In any event, enough copies were issued so that its ideas could not easily be suppressed or forgotten.

By the time the printing had got under way, Rheticus had taken a professorship at Leipzig, too far from Nuremberg to assist directly with the proofreading. Thus the printer, Petreius, turned to a local scholar and theologian, Andreas Osiander, who had helped him on at least one previous occasion.

In order to disarm criticism of the unorthodox cosmology in the book, Osiander added an unsigned introduction on the nature of hypotheses. He wrote:

> It is the duty of an astronomer to record celestial motions through careful observation. Then, turning to the causes of these motions he must conceive and devise hypotheses about them, since he cannot in any way attain to the true cause. . . . The present author has performed both these duties excellently. For these hypotheses need not be true nor even probable; if they provide a calculus consistent with the observations, that alone is sufficient. . . . So far as hypotheses are concerned, let no one expect anything certain from astronomy, which cannot furnish it, lest he accept as true ideas conceived for another purpose, and depart from this study a greater fool than when he entered it.

I doubt that Osiander's anonymity stemmed from any malicious mischievousness, but rather simply from a Lutheran reluctance to be associated with a book dedicated to the Pope. In any event, Kepler and the other leading astronomers of that century were fully aware of the authorship; in Kepler's copy, preserved at the University of Leipzig, Osiander's name has been written above the introduction. There exists a presentation copy given by Rheticus to Andreas Aurifaber, who was then Dean of the University of Wittenberg. The inscription is dated 20 April 1543. Thus a copy of the book could have easily reached Copernicus before he died on 24 May 1543, but because he had been incapacitated by a stroke, he was probably unaware of Osiander's introduction.

Rheticus himself was so offended by the added introduction that he struck it out in the copies he distributed. He also deleted the last two words of the printed title *De revolutionibus orbium coelestium*. There is an old tradition that Osiander assisted the printer in changing the title from "Concerning the Revolutions" to "Concerning the Revolutions of the Heavenly Spheres." It is difficult to see precisely what Rheticus thought was offensive about the additional words except that, like the introduction, the expression "Heavenly Spheres" perhaps suggests too much the idea of model building. As I shall explain, the idea that astronomers were merely playing some kind of geometrical game had a widespread currency in the sixteenth century, and Osiander's preface simply served to reinforce what astronomers thought they saw in the major part of *De revolutionibus*. When we notice that Copernicus used an entirely different arrangement of circles for predicting latitudes than for predicting longitudes, we realize that any reader who studied the great bulk of the book carefully would necessarily have seen Copernicus as a builder of hypothetical geometrical models.

Despite the existence of the manuscript with its many layers of revisions, and even the *Commentariolus*, which provides a glimpse of an earlier formulation, we have no definite idea of the circumstances that caused Copernicus to adopt a Sun-centered cosmology. Attempting to answer this question is one of the intriguing problems that face Copernican scholars today.

If we, as twentieth-century astronomers, were to speculate freely, we might well invent some quite convincing causes. First, we might suppose that the *Alfonsine Tables* were no longer in accord with the actual observations. This is true, but mostly irrelevant. Second, we might imagine that successive generations of theory-patching had left the Ptolemaic system too cumbersome for practical use, so that a massive simplification was in order. This second supposition is entirely false.

Let us first consider the matter of predictions versus observations. Was Copernicus motivated to reform astronomy because the current almanacs were bad? Because we can compare fifteenth-century ephemerides with the far more accurate calculations carried out recently by Dr. Tuckerman at the IBM Corporation, we know nowadays that they often had errors of several degrees. But did Copernicus know this?

Soon after Copernicus had returned to Poland from Italy, the planets put on a particularly spectacular celestial show. Saturn and Jupiter, the slowest moving planets, moved into the constellation Cancer for one of their scarce conjunctions, once in 20 years. In addition, Mars, Venus, and Mercury, and eventually the Sun and the Moon, all congregated within this single astrological sign. In the winter of 1503–1504, Mars went into its retrograde motion, making repeated close approaches to Jupiter and Saturn.

My assistant, Barbara Welther, has charted for us the geocentric longitudes of the superior planets as a function of time (Figure 2). You can see how Mars bypasses Jupiter and Saturn in October 1503, and then, as all the planets go into retrograde, Mars backs up past Saturn and Jupiter, and then passes them directly once more in the winter of 1504. We have not shown the great conjunction of Jupiter

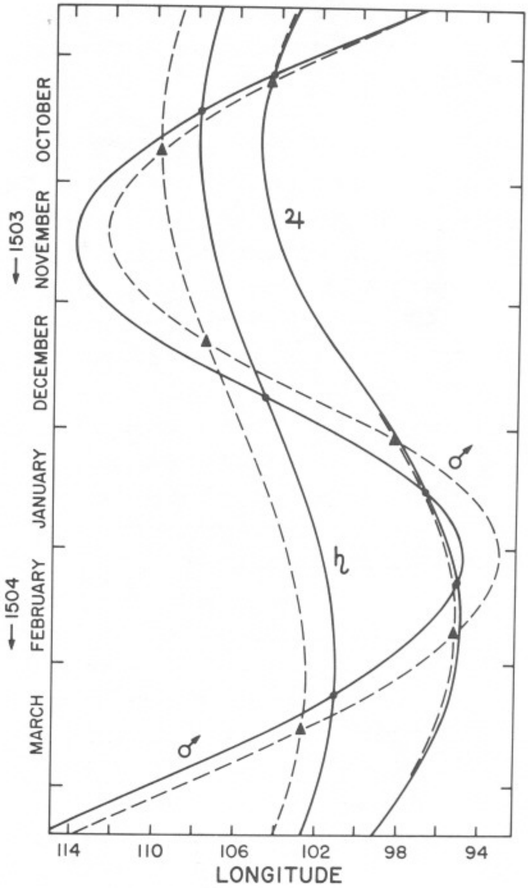

FIGURE 2. *Apparent motions of the superior planets just before the great conjunction of 1504. The solid lines and circles show the actual positions and conjunctions. The broken lines and triangles show the predicted positions and conjunctions.*

and Saturn at the end of May, because by that time they were too close to the Sun. We have marked with dashed lines the predicted positions of the planets according to the *Alfonsine Tables*. Notice particularly that in February and March the Mars predictions erred by 2° and Saturn by 1.5°, whereas Jupiter was predicted rather accurately. The

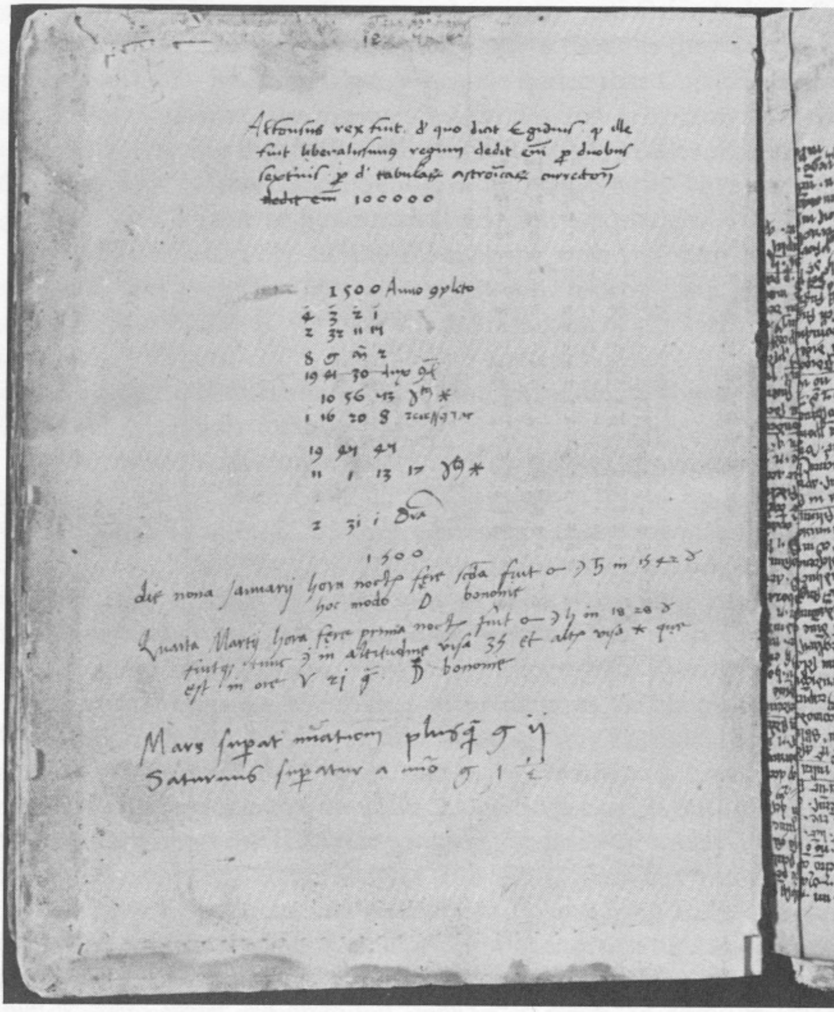

FIGURE 3. *Copernicus wrote these notes on observations at the end of his printed copy of the* Alfonsine Tables *(1492). By permission of the Uppsala University Library.*

predicted times of the conjunctions differ by about one or two weeks from the actual times shown by the intersections of the curves.

Anyone as interested in astronomy as Copernicus could scarcely have failed to observe these phenomena, but I was curious to know whether he had noticed these deficiencies in the *Alfonsine Tables*. Although there is no direct record that Copernicus made these observations, Dr. Jerzy Dobrzycki suggested to me a way whereby we can be certain that our astronomer followed the planetary motions in the year of the great conjunction. Bound in the back of his copy of the *Alfonsine Tables* are sixteen extra leaves on which Copernicus added carefully written tables and miscellaneous notes. Below the record of two observations made in Bologna in 1500, there is, in another ink, a cryptic undated remark in highly abbreviated Latin (Figure 3): "Mars surpasses the numbers by more than two degrees. / Saturn is surpassed by the numbers by one and a half degrees."

If we examine carefully the error pattern between the positions predicted for the superior planets by the *Alfonsine Tables* and the calculations made by Tuckerman, we find a virtually unique error pattern for February and March of 1504 corresponding to the note. Thus, our astronomer must have been fully aware of the discrepancies between the tables and the heavens.

Why, then, are such glaring inadequacies never mentioned by Copernicus as a reason for introducing a new astronomy? I believe the answer is quite simple. Copernicus knew very well that discrepancies of this sort could be corrected merely by changing the parameters of the old system. A new Sun-centered cosmology was hardly required for patching up these difficulties with the tables.

But furthermore, if we turn once more to the analysis made possible by modern computers, and if we examine the old ephemerides, we are shocked to discover that there is relatively little difference in the average errors before and after Copernicus. His work has scarcely improved the predictions.

Rather than condemn Copernicus, we should remember that he had no procedure for handling errors in a multiplicity of data. He had only a few score ancient observations, those recorded by Ptolemy in the *Almagest*. Since these were the minimum number required to establish the parameters, he was obliged to assume that they were perfect and to force his own parameters to fit them. From his own planetary observations he only slightly modified Ptolemy's eccentricities and apsidal lines, and he reset the mean longitude, somewhat akin to resetting the hands of a clock whose mechanism is still basically faulty. Copernicus himself must have realized that he had not achieved as much in this direction as he might have hoped, and perhaps this partly explains his reluctance to send his great work to the printer.

After *De revolutionibus* was published, Erasmus Reinhold reworked the planetary tables into a far handier form. His *Prutenic Tables* superseded the *Alfonsine Tables* remarkably quickly. This is actually very curious because, in the absence of systematic observations, nobody really knew how good or bad any of the tables were. In fact, it was not until Tycho Brahe that a regular series of observations established the inadequacies of all the tables.

Tycho himself was something of a child prodigy; when he saw an eclipse at age 13 it struck him as "something divine that men could know the motions of stars so accurately that they could long before foretell their places in relative positions." But three years later, at the great conjunction of Saturn and Jupiter in 1563, he was astonished and offended to discover that even Prutenic-based ephemerides foretold the event on the wrong day. From the time of that great conjunction onward, he kept regular observations of increasing precision that eventually became the basis for another sweeping reform of astronomy.

Let us now turn quickly to a second imagined defect in the ancient geocentric astronomy, which, if true, would give more than adequate grounds for introducing a new system. This is the story, widely repeated in the secondary literature, that by the Middle Ages the Ptolemaic theory had been hopelessly embroidered with epicycles-on-epicycles. I fear that we modern astronomers have been particularly fond of this legend because it reminds us of a Fourier series. In Ptolemy's original scheme, the Earth is placed near but not exactly at the center of a large orbital circle called the deferent. Each planet moves in a secondary circle of epicycle, which produces the retrograde motions of the sort that we have noted at the time of the conjunctions in 1504. From a modern heliocentric viewpoint we would say that the planetary epicycles are reflections of the Earth's own orbit.

About a century ago, the story began to propagate that Ptolemy's rather simple system had been overlaid with dozens of additional secondary circles. The seed for this mythology was planted by Copernicus himself when, at the end of his *Commentariolus*, he concluded: "All together, therefore, 34 circles suffice to explain the entire structure of the universe and the entire ballet of the planets." Nineteenth-century commentators used their imaginations to embellish Copernicus's simple claim. Without checking the facts, they created a fictitious pre-Copernican planetary theory hovering on the brink of collapse under the burden of incredibly complex wheels upon wheels.

I suspect that, at the end of the thirteenth century, Alfonso the Great may have contributed to the legend, because he supposedly told his astronomers that, if he had been present at creation, he could have given the Good Lord some hints. Again, modern electronic computers have helped us put this legend to rest. I have recomputed his planetary tables in their entirety to show that they are based on the classical and simple form of the Ptolemaic theory with only two or three minor changes of parameter in the whole set.

Next, I used these thirteenth-century tables to compute a daily ephemeris for 300 years, and this I compared with the best almanacs of the fifteenth and early sixteenth centuries. The comparison showed, without any question, that the leading almanac makers, such as Regiomontanus, were using the unembellished Ptolemaic theory as found in the *Alfonsine Tables*.

Is it possible that the epicycles-on-epicycles existed but simply did not get to the level of almanac making? The answer is both no and yes. From antiquity there were actually two competing cosmological views. First was the system of concentrically nested spheres, espoused by Aristotle because it made such a tidy, compact, mechanical universe. In contrast, the Ptolemaic system had large clumsy epicycles that were difficult to place in concentric nests.

Peurbach's *New Theory of the Planets*, the most important work on astronomy written in the generation immediately preceding the birth of Copernicus, added no new epicycles, but instead attempted to resolve the cosmological competition by incorporating large eccentric zones of crystalline aether. By providing something of an off-center tunnel for the epicycle, the mechanism for each planet could be contained within two concentric bounds. Thus in principle the entire planetary system of Ptolemy could be nested together within the homocentric aethereal spheres of Aristotle. Such was the *New Theory of the Planets*, and I hasten to say that this idea was not really new, as it had already been described by Islamic scientists, and proposed even earlier by Ptolemy himself.

In recent years, the historians of science have discovered that, interestingly enough, thirteenth- and fourteenth-century Islamic astronomers discussed one important case of an epicycle-on-epicycle, designed not to improve the fit to observations, but to satisfy a philosophical principle. Because this same philosophical point played a major role in the motivation of Copernicus, let me now return to his work and present the two major reasons that Copernicus himself gives as primary motivations for his astronomical work.

In the *Commentariolus*, our astronomer wrote concerning the planetary motions that "Eventually it came to me how this very difficult problem could be solved with fewer and much simpler instructions than were formerly used, if some assumptions were granted me." If we

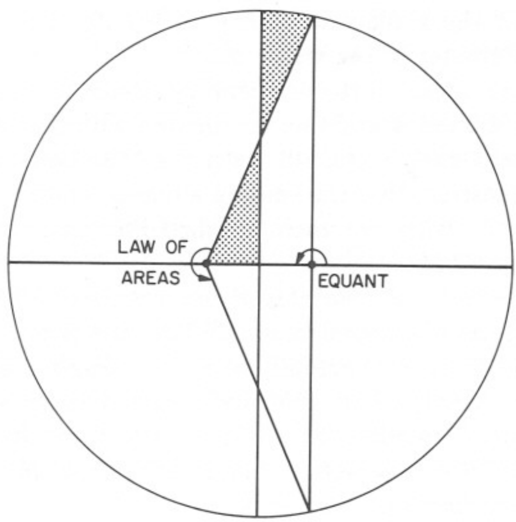

FIGURE 4. *The near-equivalence of the equant and the law of areas.*

put aside the spurious relevance of counting circles, the heliocentric system does provide a profound simplification, and I must necessarily return to this point before the end of the paper. However, Copernicus awarded virtually equal weight to a second philosophical principle, the Platonic-Pythagorean concept of uniform circular motion. Copernicus opened his *Commentariolus* with an attack on the Ptolemaic equant, which appeared to violate this principle of uniform circular motion. The equant is a seat of uniform circular motion placed equal and opposite to the Earth within the deferent circle; it drives the epicycle around on the deferent more swiftly at the perigee than at the apogee.

Figure 4 illustrates the relation between Kepler's law of areas and the equant; because the equant turns uniformly, the planet will move in equal time in each of the four quadrants. The law of areas tells us that the planet will move through these same arcs in equal times provided that the areas swept out from the primary focus are equal. Because the equant is at the empty focus, the shaded triangles are virtually equal except that the upper one has a curved side; to this extent, the equant is a good approximation to the true motion, espe-

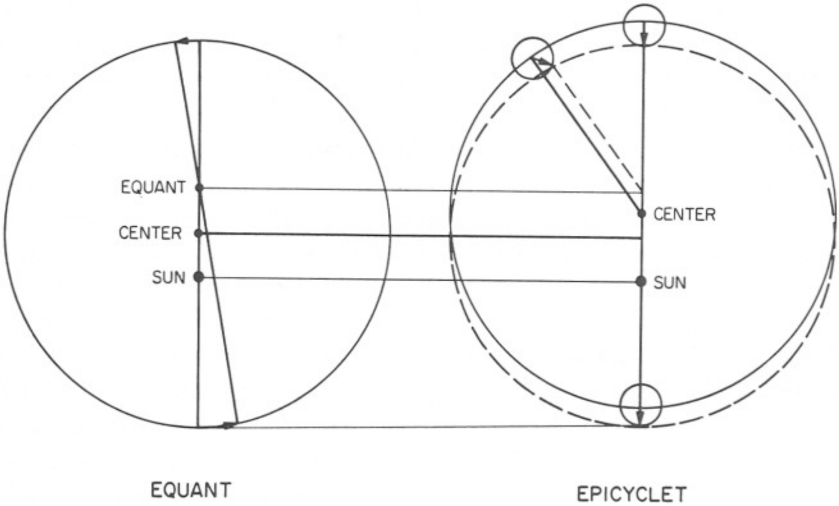

FIGURE 5. *Copernicus's replacement of the equant by a pair of uniform circular motions. The epicycle has a radius of* e/2 *and always moves to form the isosceles trapezoid shown above.*

cially at the quadratures. As Kepler was later to show, the major discrepancy occurs in the octants.

In any event, Copernicus despised the equant and he felt that Ptolemy had cheated by introducing it. Figure 5 shows how Copernicus replaced the equant with an eccentric circle and a small epicyclet. In the *Commentariolus* he preferred to use a concentric circle with a double epicyclet, which was precisely the same mechanism suggested two centuries earlier by Ibn ash-Shātir in Damascus; whether there was any transmission from those Islamic astronomers to Copernicus is still debatable. After Copernicus discovered the motion of the planetary apsidal lines, it became more convenient to use the eccentric circle and single epicyclet shown here. I shall not take the time here to explain the equivalence between this mechanism and the equant, but I shall simply say that the great bulk of the *De revolutionibus* involves the use of this mechanism.

Nowadays the epicyclet seems esoteric and forgettable. When we commemorate Copernicus, we praise his profound insight in seeing the philosophical and aesthetic simplicity of his system, but we try to ignore his infatuation with the second, very deceptive principle of uniform circular motion. I should now like to demonstrate that Copernicus's sixteenth-century successors, living in an age long before Newtonian dynamics, evaluated these philosophical principles in precisely the opposite way, rejecting the simplicity of the heliocentric cosmology but admiring the epicyclets.

About 1971, I had an interesting discussion with another Copernican scholar, Dr. Jerome Ravetz, and we asked ourselves if *De revolutionibus* actually had any careful readers. We speculated that there are probably more people alive today who have read this book carefully than in the entire sixteenth century. I have already introduced some of the candidates for that early era: Georg Rheticus, the Wittenberg scholar who persuaded Copernicus to publish his book; Erasmus Reinhold, the Wittenberg professor who stayed home but who later composed the *Prutenic Tables*; and Tycho Brahe, the great Danish observer. Others would include Johann Schöner, the Nuremberg scholar to whom Rheticus addressed the *Narratio prima*; Christopher Clavius, the Jesuit who engineered the Gregorian calendar reform; Michael Maestlin, Kepler's astronomy teacher; and Johannes Kepler himself.

At that time I was on a sabbatical leave from the Smithsonian Astrophysical Observatory, and two days after talking with Dr. Ravetz I happened to visit the remarkable Crawford collection of rare astronomical books at the Royal Observatory in Edinburgh. There I admired one of their prize possessions, a copy of the first edition of *De revolutionibus*, legibly annotated in inks of several colors. As I examined the book, I deduced that the intelligent and thorough notations were undoubtedly made before 1551, that is, within eight years after its publication. Our speculation from two days earlier seemed completely demolished, because it appeared that if intelligent readers were so rare, it would be unlikely that the very next copy of the book that I saw could be so carefully annotated. But then a second thought crossed my mind: Perhaps the Crawford copy had been annotated by one of the handful of astronomers we had mentioned. The list quickly narrowed to Rheticus, Reinhold, and Schöner, the only ones active before 1550. Internal evidence suggested Erasmus Reinhold, and although his name is not in the book, I soon found his initials stamped into the decorated original binding. Ultimately I was able to obtain additional specimens of Reinhold's distinctive handwriting, which settled the matter beyond all doubt.

One of the most interesting annotations in Reinhold's copy appears on the title page, where he has written in Latin "The axiom of astronomy: Celestial motion is uniform and circular or composed of circular and uniform parts." Reinhold was clearly fascinated by Copernicus's epicyclets and his adherence to the principle of circular motion. The paucity of annotations in the first twenty pages, which Copernicus devoted to the new cosmology, shows that Reinhold was not particularly interested in heliocentrism. Accepting Osiander's statement that astronomy was based on hypotheses, Reinhold was apparently intrigued by the model-building aspects. Whenever alternative mechanisms for expressing the motions appeared in the book, he made conspicious enumerations with Roman numerals in the margins.

Because Reinhold published the *Prutenic Tables*, naming them in part for Copernicus, he is sometimes listed as an early adherent of the heliocentric cosmology. However, the nature of the tables makes them independent of any particular cosmological system, and although his introduction is full of praise for Copernicus, he nowhere mentions the heliocentric cosmology. With his great interest in hypothetical model building, there's reason to suspect that Reinhold was on the verge of an independent discovery of the Tychonic system; unfortunately, he died of the plague at an early age before he could consolidate any cosmological speculations of his own.

Flushed with the success of identifying Reinhold's copy, I resolved to examine as many other copies of the book as possible in order to establish patterns of readership and ownership, always hoping to find further interesting annotations. For three years I have systematically examined copies in such far-flung places as Budapest and Basel, Leningrad and Louisville, Copenhagen and Cambridge. In the process I saw and photographed several particularly interesting copies, including the *De revolutionibus* owned by Michael Maestlin, preserved in Schaffhausen, Switzerland; this is one of the most thoroughly annotated copies in existence. I also examined copies once owned by Rheticus, by Kepler, and by Tycho Brahe—the last being a heavily annotated second edition in Prague. In all, I had managed to see 101 copies by the spring of 1973. The investigation confirmed that the book had rather few perceptive readers, at least among those who read pen in hand. Despite this, however, the book seems to have had a fairly wide circle of casual readers, much larger than generally supposed.

In May of 1973, I had the opportunity to visit Rome, where there were seven copies of the first edition that I had not examined. My quest took me first to the Vatican Library, where I went armed with shelf mark numbers provided by Dr. Dobrzycki. Some of the books in the Vatican Library came there with the eccentric Queen Christina of

Sweden, who abdicated her throne in 1654, abandoning her Protestant kingdom for Rome. Her father, Gustavus Adolphus, had ransacked northern Europe during the Thirty Years' War and among other things had captured most of Copernicus's personal library. Dr. Dobrzycki had gone to Rome in search of Copernican materials that Queen Christina might have taken along. In the Vatican, he found an unlisted copy of Copernicus's book among the manuscripts, that is, a third copy beyond the two examples cataloged among their printed books. Fortunately, Dr. Dobrzycki gave me the number for the volume, which could not have been found in any of the regular Vatican catalogs.

When I examined this copy, I recognized that the extensive marginal annotations must have been made by a highly skilled astronomer. At the end were 30 interesting manuscript pages, full of diagrams made by someone working along the same lines as Tycho Brahe, and dated 1578. Although there was no name any place on the volume, I quickly conjectured that the annotations had been made by the Jesuit astronomer Christopher Clavius. In the first edition of his learned *Commentary on the Sphere of Sacrobosco*, published in 1570, he failed to mention Copernicus. But in the third edition, published in 1581—after the time these manuscript notes were written—he commented rather extensively and wrote "All that can be concluded from Copernicus's assumption is that it is not absolutely certain that the eccentrics and epicycles are arranged as Ptolemy thought, since a large number of phenomena can be defended by a different method."

In a state of considerable excitement, I contacted Dr. D. J. K. O'Connell, former Director of the Vatican Observatory, and with his help I obtained Xerox copies of two Clavius letters from the Jesuit Archives. I eagerly returned to the Vatican Library, only to have my hypothesis smashed within a few minutes. There was no possibility that the handwriting in the *De revolutionibus* could be that of Christopher Clavius.

I left Rome in a baffled and troubled state for a Copernicus conference in Paris. There, by a fantastic stroke of luck, I received the new Prague facsimile of the second-edition *De revolutionibus* with the annotations by Tycho Brahe. I think my heart must have skipped a beat when I saw the handwriting in the facsimile, because I then realized that the first edition in Rome was probably also in Tycho's hand. What I had discovered was the original working copy, probably the most important Tycho manuscript in existence. The example in Prague was a derivative copy, being annotated by Tycho for possible publication. I rebooked my flights, went back to Rome, and after I put the Prague facsimile side by side with the Vatican copy, it took only a few minutes to prove my conjecture. Afterward, the Vatican librarians traced the book to Queen Christina, who must have gained possession of it in 1648 when her troops captured the collections founded by Rudolf II in Prague.

Of many remarkable things about this copy, the first appears on the title page itself. We find the very same words that Reinhold had inscribed on the title page of his copy, "The axiom of astronomy: Celestial motion is uniform and circular, or composed of uniform and circular parts." I had already known that Tycho Brahe had visited Wittenberg on at least four occasions, and that, in 1575, three years before the dated annotations in this book, he had visited Reinhold's son and had seen Reinhold's manuscripts. In an article that I had written earlier for the Copernicus celebrations in Toruń, I had stated "We are tempted to imagine that Tycho's own cosmological views grew from seeds planted at Wittenberg by a tradition that honored Copernicus, but which followed Osiander's admonition that it is the duty of the astronomer to 'Conceive and devise hypotheses, since he cannot in any way attain the true causes'." [2] The newly found Tycho copy dramatically confirms this intellectual heritage, not only through this motto on the title, but within the book, where numerous annotations are copied word for word from Reinhold's copy. In particular, Tycho, like Reinhold, specifically numbered any alternative arrangements of circles indicated by Copernicus.

In the Tycho Brahe manuscript bound at the end of the Vatican *De revolutionibus*, the first opening is dated January 27, 1578, the day after the spectacular comet of 1577 had been seen for the last time. The diagrams on those two pages are heliocentric, and a note in the corner indicates that it was drawn according to the third hypothesis of Copernicus. In the next two weeks, Tycho explored additional heliocentric arrangements for the planets and geocentric models for the Moon. On February 14 and 15, he began to investigate *geocentric* constructions for Venus and Mercury, especially alternate positions of the single epicyclet for Venus and the pair of epicyclets for Mercury. He specifically noted that "This new idea occurred to me on February 13, 1578."

Three days later Tycho drew the most interesting diagram of the entire sequence, a proto-Tychonic system with the Earth at the center circled by the Moon and the Sun (Figure 6). Around the Sun are the orbits of Mercury and Venus. The three superior planets are still ar-

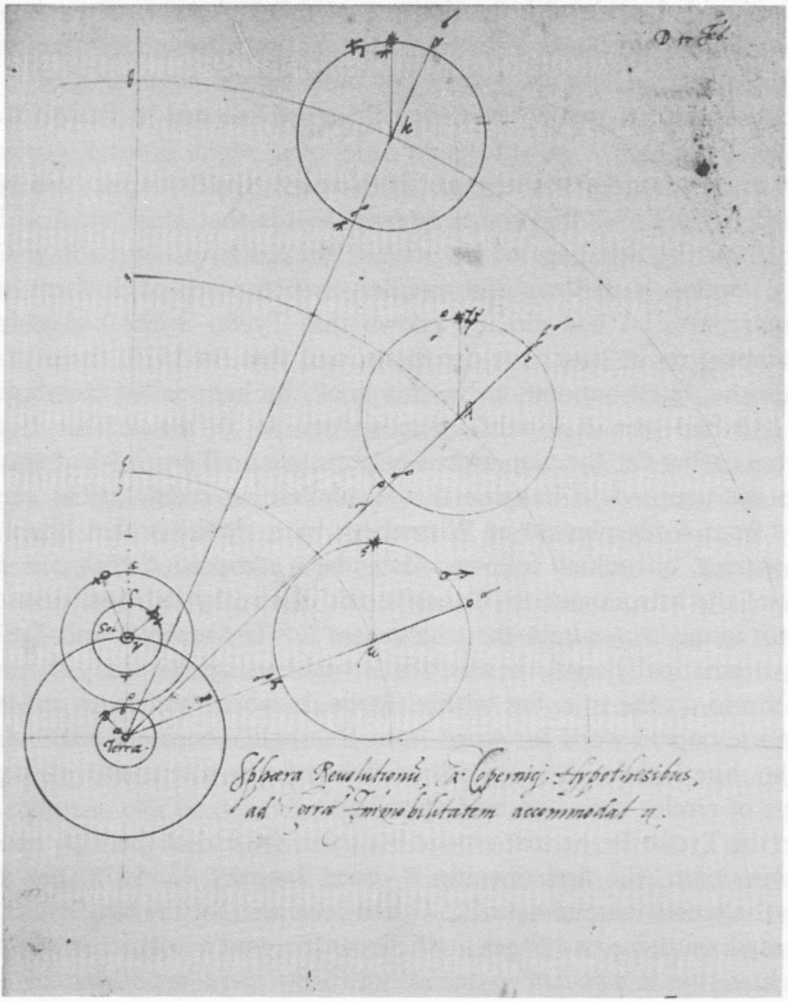

FIGURE 6. *Tycho's sketch of a geocentric planetary system, fol. 210v in the manuscript notes bound at the end of his annotated copy of* De revolutionibus *(1543), Vatican Library Ottob. 1901.*

ranged in circles about the Earth, but each epicycle has been drawn the same size as the Sun's orbit. To finish the construction of the Tychonic system, it is necessary only to complete the parallelograms for Mars, for Jupiter, and for Saturn. Tycho was now surely within grasp of his final system. But notice the caption: "The spheres of revolution accommodated to an immobile Earth from the Copernican hypotheses." Here we see Tycho playing the astronomical geometry game, greatly under the influence of Copernicus, and somehow supposing that a geocentric system is compatible with the teachings of the master.

It is very curious that Tycho did not publish his new system until a decade later. Tycho was a dynamic young man of 31 when he wrote this manuscript, already well established on the island of Hven, but perhaps still uncertain where his observations for the reform of astronomy would lead him. A passage in his book implies that he did not establish the Tychonic system until around 1583, five years after he drew these diagrams. I can only suppose that these five years were an important time of maturing. In that interval, Tycho must have speculated on the movement of the Great Comet of 1577, realizing that it would have smashed the crystalline spheres of the ancient astronomy, had they existed. Perhaps he began to look for greater certainty in astronomy and to suppose that, after all, the observations made with his giant instruments at his Uraniborg Observatory could lead beyond hypothesis to physical reality. If so, like his contemporaries in that pre-Newtonian, predynamical age, he must have viewed the physics of the sluggish, heavy Earth as a most important phenomenon to be preserved. Concerning the Copernican system, Tycho Brahe wrote: "This innovation expertly and completely circumvents all that is superfluous or discordant in the system of Ptolemy. On no point does it offend the principle of mathematics. Yet it ascribes to the earth, that hulking, lazy body, unfit for motion, a motion as quick as that of the aethereal torches, and a triple motion at that." I can well imagine that Tycho believed he was making a great step forward toward understanding the physical reality of the universe when he adopted his own geocentric system.

To us, the Tychonic system looks clumsy and wrong. To us, there is something more neat and orderly about the heliocentric system. Indeed, it is precisely this elegant organization that Copernicus found pleasing to the mind, and that led to his cosmology. In a powerful plea for the heliocentric world view near the beginning of *De revolutionibus*, Copernicus wrote:

> At rest in the middle of everything is the Sun. For in this most beautiful temple, who would place this lamp in another or better position? From here it can light up the whole thing at the same time. Thus as though seated on a royal throne, the Sun governs the family of planets revolving around it. In

> this arrangement, therefore, we discover a marvelous commensurability of the Universe, and an established harmonious linkage between the motion of the spheres and their size, such as can be found in no other way. Thus we perceive why the direct and retrograde arcs appear greater in Jupiter than in Saturn and smaller than in Mars, and why this reversal in direction appears more frequently in Saturn than in Jupiter, and more rarely in Mars and Venus than in Mercury. All these phenomena proceed from the same cause, which is the Earth's motion. Yet none of these phenomena appears in the fixed stars. This proves their immense height, which makes the annual parallax vanish from before our eyes.

There is a whiff of reality here, especially in the resounding conclusion, "So vast, without any question, is this divine handiwork of the Almighty Creator." Yet very few people in the sixteenth century grasped the harmonious, aesthetic unity that Copernicus saw in the cosmos. And that is why we must also salute another perceptive genius, born almost a century later than Copernicus. Like Copernicus, Johannes Kepler saw the Sun seated upon its royal throne as the governor of the planetary system, and he tried mathematically to find the harmonious linkage between the motions of the spheres and their sizes. To us Kepler's neo-Platonic attempts to find an archetypal geometrical structure in the planetary arrangement smack of mystical numerology—yet this is hardly a criticism, considering that numerology has not been banished from modern cosmology. But more important, Kepler saw in the Copernican arrangement of the planets about the Sun the real possibility of a celestial physics, and he made the first groping steps toward a dynamics of the heavens—a dynamics that, reshaped and powerfully formulated by Isaac Newton, ultimately proved to be the primary justification for the heliocentric universe.

Although Copernicus is not celebrated for his observations, it was in the Copernican tradition that Kepler and Galileo taught us to use our senses to distinguish between the various hypothetical world views, leaving only those consistent with the observations. In a way we are still model builders, as Osiander suggested, but unlike Andreas Osiander and Erasmus Reinhold, we are no longer content to entertain alternatives without trying to choose one as physically most acceptable. Modern science still plays its games, but in an entirely different way than did the ancient and medieval astronomers. Certainly Copernicus, Tycho, Kepler, Galileo, and Newton are heroes in this epic reformation in our understanding of what nature is and what learning and observation should be.

Although I have said perhaps too much about the technical astronomy of Copernicus and rather little about his cosmology, I hope that within this broader context you have been able to appreciate all the more how unique was Copernicus's own intellectual adventure. Only in our own generation have we been able to break the terrestrial bonds; men flung out toward the Moon have seen the spinning Earth, a blue planet, sailing through space. Although rejected by the astronomers of his day, the Copernican idea became the point of departure for the law of universal gravitation. In reality, the Copernican quinquecentennial celebrates the origins of modern science and our contemporary understanding of the universe. In setting the Earth into motion, Copernicus was right: his daring idea still guides the unfinished journey of modern science.

Mathematical Postscript

That the Copernican scheme of an eccentric deferent and a single epicyclet satisfies Keplerian motion to the first power of the eccentricity can be elegantly demonstrated as follows. If we neglect terms of e^2 and higher, the law of areas becomes

$$r^2\theta = na^2(1-e^2) = na^2$$

where we have for the mean motion $n = 2\pi/P$; similarly the equation for the ellipse is

$$r = \frac{a(1-e^2)}{1-e\cos\theta} = a(1+e\cos\theta)$$

where a is of course the semimajor axis. After combining these equations, integrating, and inverting, we find

$$\theta = nt - 2e\sin nt.$$

With a little trigonometric manipulation and by discarding terms in e^2 and higher, we have

$$x = r\cos\theta = a(\cos nt + \tfrac{3}{2}e - \tfrac{1}{2}e\cos 2nt)$$

$$y = r\sin\theta = a(\sin nt - \tfrac{1}{2}e\sin 2nt).$$

These equations correspond to motion with period P in circle of radius a displaced by $\frac{3}{2}\,ae$ from the sun, together with a circular epicyclet of radius $\frac{1}{2}\, ae$ and period $\frac{1}{2}\, P$. This is essentially the model for planetary longitude adopted by Copernicus in his *De revolutionibus*, although he did not strictly maintain the 3:1 ratio between the displacement of the main circle and the radius of the epicyclet. (For example, the Copernican ratio for the Mars model is 2.92:1).

I should like to acknowledge the late Sir Harold Jeffreys, who showed me this demonstration without realizing how precisely it described the Copernican model.

Notes and References

[1] Professor Edward Rosen's Copernican biography in his *Three Copernican Treatises* (New York, 1971) has provided an authoritative source for details of Copernicus's life, and I have borrowed from him several felicitous turns-of-phrase as well as English translations of some of the Latin texts (which I have generally abridged). Other writings that have been particularly stimulating include J. Ravetz, *Astronomy and Cosmology in the Achievement of Nicolaus Copernicus* (Wroclaw, 1965), P. Duhem, *To Save the Phenomena* (Chicago, 1969), and L. A. Birkenmajer, *Mikolaj Kopernik* (Cracow, 1900) (English translation under joint preparation by J. Dobrzycki and myself). Also useful are A. Koyré, *The Astronomical Revolution* (Paris, 1973) and *The Great Books of the Western World* (Chicago, 1952) volume 16, which contains an English translation of *On the Revolutions* as well as Ptolemy's *Almagest*.

[2] Reprinted as selection 13 of this anthology; see esp. p. 246. The reader is reminded that we now know that the annotations in the Vatican and Prague copies of *De revolutionibus* are not by Tycho Brahe, but by Paul Wittich—see the Preface to this anthology.