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By

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THE EXACT SCIENCES IN LUTHERAN GERMANY AND TUDOR ENGLAND

A Dissertation APPROVED FOR THE
DEPARTMENT OF THE HISTORY OF SCIENCE

BY

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CONTENTS

ILLUSTRATIONS

ABBREVIATIONS

Almagest	Ptolemy. *Almagest*. Translated by G. J. Toomer. New York: Springer-Verlag, 1984
CR	Melanchthon, Philip. *Corpus Reformatorum Philippi Melanthonis Opera quae supersunt omnia*. Edited by Carolus Gottlieb Bretschneider. 28 volumes. Frankfurt am Main: Minerva, 1834-1900; reprint, New York: Johnson Reprint, 1963-1964.
De rev. (1543)	Copernicus, Nicolas. *De revolutionibus orbium coelestium, Libri VI*. Nuremberg: Ioh. Petreius, 1543.
DNB	*Oxford Dictionary of National Biography in Association with the British Academy: From the Earliest Times to the Year 2000*. Edited by H. C. G. Matthew and Brian Harrison. Oxford: Oxford University Press, 2004.
DSB	*Dictionary of Scientific Biography*. Edited by Charles Gillispie. New York: Charles Scribner's Sons, 1970- .
GCNS	Randles, W. G. L. *Geography, Cartography and Nautical Science in the Renaissance: The Impact of the Great Discoveries*. Aldershot: Ashgate Variorum, 2000.
HAMA	Neugebauer, Otto. *A History of Ancient Mathematical Astronomy*. New York: Springer-Verlag, 1975.
JHA	*Journal for the History of Astronomy*
NP (1540)	Rheticus, Georg Joachim. *Ad clarissimum virum D. Ioannem Schonerum, de libris revolutionum . . . NARRATIO PRIMA*. Danxig: Franciscus Rhodus, 1540.

ABSTRACT

This dissertation compares the astronomical works of two sets of writers in the sixteenth century: university professors in Lutheran territories, and mathematical practitioners and popularizers in Tudor England. The opening chapters establish the intellectual and institutional context by summarizing the development of the western astronomical tradition, including the place of mathematics in the university. Special attention is given to three problems in astronomy and the solutions proposed by Claudius Ptolemy and Nicolaus Copernicus: the prediction of the apparent motion of the Sun; the correct arrangement of stars and planets; and the measurement of the distances from Earth to the Sun, Moon, and other celestial objects. The educational reforms of Philip Melanchthon, who believed that divine providence manifested itself especially clearly in astronomy, ensured that Wittenberg and other Lutheran universities produced a number of highly competent and creative astronomers.

The next two chapters examine the early responses to Copernicus at Wittenberg and the ongoing efforts among Melanchthon's followers to incorporate Copernican astronomy into the curriculum. Lutheran mathematicians agreed that Copernican models were superior in some respects to existing astronomical models, but most looked for ways to convert his controversial heliocentric cosmology to a geocentric framework. Both the geocentric majority and the tiny group of heliocentrists expected that a complete course of astronomical studies would include both Ptolemaic and Copernican models.

The final chapters shift focus to England, where a revival of mathematical

education was underway by mid-century. In this section, astronomy is defined broadly to include astronomical navigation, since the potential economic and political benefits of undertaking voyages of discovery provided part of the justification for mathematical studies. Elizabethan authors frequently cited and even translated Lutheran works, suggesting that Lutheran influence played an important role in the English mathematical renaissance. Most readers turned to Lutheran sources for technical guidance, in part because Melanchthon's followers had produced the leading works on Copernican astronomy. A smaller group, including some of the leading Tudor mathematicians, also adopted Melanchthon's providential reading of astronomy. Thus, English mathematical practitioners were not intellectually isolated, but form part of a continuous tradition that began in Wittenberg.

CHAPTER ONE

INTRODUCTION

Any college textbook or survey of science in early modern Europe is likely to mention several English mathematicians of the seventeenth century--such as Edmund Halley, Robert Hooke, and of course Isaac Newton--whose suitability for inclusion meets with ready acceptance. The originality of their ideas and their fame among contemporaries ranks them among the scientific superstars of their day. But turn back a hundred years, and a very different picture presents itself to the reader, packed with luminaries from Germany and Italy and strange nationalities the typical American reader cannot locate on a map. There is Thomas Digges, the first English Copernican, with his picture of a Sun-centered system embedded in an infinite expanse of stars. There is perhaps John Dee, who must have been important although what exactly he did never becomes clear. And there may be a list of “also-rans” who merit recognition for having written something, but who did nothing original enough to warrant any description, which would take precious space from Copernicus or Descartes.

Many of the specialized studies that might be expected to shed some light on English science in the sixteenth century actually approach the astronomy of the time as necessary background for understanding English literature. Digges plays a supporting role for a story about Donne, Dee for Spenser, and so on, but rarely if ever do the scientific writers win lead parts, nor is their own curiosity about the world subjected to the same investigation as that of a playwright or poet. The small number of studies taking English science itself as their focus tend to agree that most of the mathematical practitioners come from the second half of the sixteenth century. For whatever reason, the English revival of letters extended to include astronomy and the other exact sciences. Such studies have tended, however, to treat their historical figures as though they were isolated intellectually as well as geographically. The existence of debts to continental figures has scarcely been acknowledged, and the nature and extent of those debts is little known.

This dissertation investigates one aspect of the late-sixteenth-century upsurge in English involvement in the exact sciences, specifically in the allied arts of astronomy and celestial navigation. I maintain that the English were heavily reliant for their knowledge of astronomy on the works of mathematicians in Lutheran Germany, whom they read, imitated, and even translated with surprising frequency. The Lutherans had recently engineered their own renaissance of mathematics, during which they made an unexpected discovery that helped to bring their work to the attention of the English and everyone else. Their discovery was the astronomy of Nicolaus Copernicus, putting the Lutherans in a unique position to offer the best and latest in mathematical astronomy, at least for a time. To understand English astronomy requires that we first understand astronomy as it was practiced at Lutheran universities; therefore, this dissertation is about Germany as much as England. I have provided expositions of certain astronomical models used by Ptolemy and their Copernican equivalents in order to provide the context for the citation by both groups of key parameters from one or another authority, because I wish to establish not just the fact that such parameters were used, but also why.

Chapter 2 begins the story with the classical astronomical tradition and its development through the Middle Ages into the early sixteenth century. The primary goal of Greek mathematical astronomy is the prediction of the angular positions of the planets, and the most fundamental Ptolemaic model is the model for the Sun. Because of its primacy, its utility for astronomical navigation, and its importance in Copernican astronomy in coming chapters, I give special attention to Ptolemy's solar model. After appropriating ancient mathematics, Islamic astronomers carried out their own observations and modified the models they inherited from Antiquity. Although space does not allow for even a brief survey of Islamic astronomy, I examine one contribution in this chapter that will become important to later European astronomy, the trepidation model affecting the motion of the fixed stars. Shortly after the recovery of ancient learning began in the Latin West, the rise of universities around the thirteenth century created a market for textbooks to teach astronomy in the classroom. The curriculum that developed centered on the use of introductory and advanced textbooks called *sphaera* and *theorica planetarum*. This phase of the story concludes with humanist and reformer Philip Melanchthon, one of Martin Luther's strongest supporters at Wittenberg. Believing that both astronomy and astrology manifest God's providential design of the world, Melanchthon promoted mathematical studies at Lutheran universities, ensuring that Germany would produce many prominent astronomers in the coming decades.

Chapter 3 turns to a lesser-known problem of mathematical astronomy, the measurement of the celestial orbs, and the related cosmological issue of the arrangement of the planets. Greek mathematicians developed a method for measuring distances of the

Sun and Moon from Earth, but the exact range of distances depended on which astronomical model was used. Astronomers knew of no method for measuring distances to the remaining planets directly, but attempted to assign distances based on sometimes arbitrary assumptions. In the early sixteenth century Copernicus worked out a Sun-centered system of astronomy that provided new solutions to several standing issues, including planetary distances. The heart of this chapter is a detailed exposition of the motion of the Earth as it is described in Copernicus' masterpiece *De revolutionibus orbium coelestium*, corresponding to the motions of the Sun and fixed stars in Ptolemaic astronomy. Although I do not discuss the derivation of the model from observation, my discussion of the connection between elements of the model and the celestial motions they generate is far more detailed than the summary treatments in most histories of astronomy. Acquaintance with the key parameters and the appearances predicted by Copernican astronomy is essential for a full appreciation of its reception in Lutheran Germany and Tudor England.

In chapter 4 I discuss three early responses to Copernicus. The first is Georg Rheticus, a student of Melanchthon who became a mathematics professor at Wittenberg and soon after a supporter of Copernicus. Rheticus wrote the first published description of Copernican astronomy and arranged the publication of *De revolutionibus*. Most of the chapter is devoted to his main work, the *Narratio prima*, in which he summarized the advantages of Copernicus' planetary models and of the heliocentric system. The reception of *De revolutionibus* among other Lutheran mathematicians generally followed the paths defined by Rheticus, even though few assented to terrestrial motion. I also offer a new interpretation of a difficult passage in the *Narratio* linking an element of

Copernican solar theory to world history. The second figure is Martin Luther, who made a brief but famous comment about the Earth's motion around the time of Rheticus' discovery. The comment is generally interpreted as an indictment of Copernicus on religious grounds, but in fact it is so vague that we cannot identify Luther's target. The third figure is Melanchthon himself, who condemned Copernicus in his physics textbook *Initia doctrinae physicae*. Both the passage on Copernicus and its modification in a later edition are discussed.

Chapter 5 extends my treatment of Lutheran astronomy to three professors of mathematics, all followers of Melanchthon, whose careers spanned the time from publication of *De revolutionibus* to the early seventeenth century. Erasmus Reinhold, Rheticus' senior colleague at Wittenberg, set an example for the majority of Lutheran astronomers by showing a neutral attitude towards heliocentrism. Yet he praised Copernican models where they could be accommodated to geocentrism and prepared the *Prutenic Tables*, based on *De revolutionibus*, that served to promote the new astronomy. Caspar Peucer, Melanchthon's son-in-law and informal successor at Wittenberg, clearly rejected heliocentrism but, like Reinhold, believed that Copernican models should be an integral part of university studies. Michael Maestlin, an early Copernican who spent most of his career at Tübingen, taught both Ptolemy and Copernicus to his students. Taken together, their works, and that of their colleague Rheticus, show an increased rigor in the mathematical curriculum compared with their medieval counterparts. As part of that, we find the matter-of-fact expectation that a complete course of astronomical studies will include Copernican astronomy, regardless of the author's preferred cosmology. Melanchthon's influence can be detected in their desire to investigate the true nature of the heavens, as far as astronomy allows.

In chapter 6 I shift focus from the Lutherans to the English. The new art of astronomical navigation enters the picture at this point, since it was of interest to an island nation but not to landlocked German professors. New navigational techniques appeared in Europe during the Renaissance, spurred on in part by Portuguese voyages down the coast of Africa and far into the Atlantic Ocean. The new phase of European exploration depended on locating the ship by using celestial objects as reference points, first the circumpolar stars, then the Sun as well. Pilots had to become mathematical practitioners with enough understanding of solar and lunar theory to consult astronomical tables. Some popular books printed in England during the late fifteenth and early sixteenth centuries contained a smattering of astronomy or cosmology, but the first true astronomical textbooks did not appear until the 1550s. Among them was an introduction to astronomy by Robert Recorde, author of a series of mathematical textbooks. Recorde was familiar with Lutheran astronomy and echoed its theological approach. After a short burst of activity at the turn of the sixteenth century, English voyages of exploration were nearly nonexistent, but they started up in earnest in the 1550s. Recorde intended some of his textbooks, including the astronomy primer and an unwritten geographical work, to be used to teach navigation for the first English trading company, the Muscovy Company.

Chapter 7 comprises several episodes in Marian and Elizabethan English mathematics. Richard Eden's translation of a Spanish navigational treatise rounds out the first phase of English reception of nautical astronomy. Although the English continued to be partly reliant on foreign pilots, they were increasingly able to train their own pilots and to make original contributions to the art of navigation. English astronomy of this period drew heavily on Lutheran sources. Some practitioners appear to have been reading for mathematical content, as they passed over the theological approach in silence. Such is the case with an ephemeris based on Reinhold's *Prutenic Tables*, and with translations of works by Peucer and Maestlin. Others clearly found Melanchthon's providential reading of astronomy appealing, without necessarily adopting his theology in other areas. This small group of English followers of Melanchthon includes two leading Tudor mathematicians, Leonard and Thomas Digges. Thus, the most important English practitioners of the exact sciences discussed in chapters 6 and 7 were not intellectually isolated, but form part of a continuous tradition starting in Wittenberg as described in chapters 4 and 5.

I have reserved an extended historiographical analysis for my concluding chapter. In chapter 8 I assess selected classic and recent works in two overlapping areas of study in early modern science, namely religion and science and the history of astronomy, in light of my own research for this dissertation. Melanchthon's influence on the history of science is an especially promising area of study because of his clearly defined theological attitude toward nature, his close involvement with educational reform, and his close connections to a core group of scientists. Such features are rarely present in the better known theologians who have attracted most attention from historians of science. This dissertation shows that Melanchthon's influence crossed confessional divides and had a profound if sometimes indirect effect on astronomy during the Reformation.

CHAPTER 2

THE GREEK ASTRONOMICAL TRADITION AND PHILIP MELANCHTHON'S EDUCATIONAL REFORM

The dominant worldview described in this dissertation can be called "Aristotelian-Ptolemaic," which is to say that it combined the general cosmology and physical explanations of Aristotle with the astronomy and mathematical methodology of Ptolemy. Even the most radical mathematicians framed their ideas in terms established by these two authorities. It was not always so, despite the fact that scholarly beliefs about the world shared points of continuity. Europeans of the early Middle Ages adopted Neoplatonic philosophy and knew of Ptolemy and Aristotle virtually by reputation alone. The rediscovery of a vast part of the ancient scientific corpus in the twelfth and thirteenth centuries constitutes a major event in the history of astronomy in the West.

In this chapter and the next I discuss the Greek astronomical tradition and its impact on two major authors of the sixteenth century, Philip Melanchthon (1497-1560) and Nicolaus Copernicus (1470-1540). The division is thematic rather than chronological. This chapter focuses on one of the main research issues in Ptolemaic astronomy, the prediction of the apparent positions of celestial bodies when viewed from the Earth, and its influence on Melanchthon's thought. The next focuses on a research issue that has received less historiographic attention, namely the determination of the true arrangement of the planets and their sizes and distances, along with the role of both branches of astronomy in the work of Copernicus. Reactions to the new solution to the new solutions for these astronomical problems expressed by contemporaries of Melanchthon and Copernicus and by the generations immediately following constitute a dominant theme in the remainder of the dissertation.

This chapter is divided into four parts. First, I summarize the Greek astronomical tradition and describe some of the elements of technical astronomy. My discussion in the first part is neither comprehensive nor original; it follows the general outline of history in surveys of the history of science and specialized histories of astronomy by David Lindberg, Olaf Pedersen, Otto Neugebauer, and James Evans.[1] Next, I examine the place of astronomy in the study of the natural world, both as a prestigious branch of mathematics and as one of the liberal arts, subordinated to physics yet capable of making meaningful statements about the world. Third, I discuss certain medieval and Renaissance astronomical textbooks written as a result of the rediscovery of Ptolemy. Finally, I turn to the reformer Melanchthon and his work to incorporate the rigorous study of Ptolemaic astronomy into the university curriculum. In the last section I adopt Sachiko Kusukawa's analysis of mathematics in Melanchthon's thought, but extend it to material not given close attention in her main study of the reformer.[2]

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[1] David C. Lindberg, *The Beginnings of Western Science: The European Scientific Tradition in Philosophical, Religious, and Institutional Context, 600 B.C. to A.D. 1450* (Chicago: University of Chicago Press, 1992); Olaf Pedersen, *Early Physics and Astronomy: A Historical Introduction*, 2nd ed. (Cambridge: Cambridge University Press, 1993); Otto Neugebauer, *The Exact Sciences in Antiquity*, 2nd ed. (New York: Dover, 1969); James Evans, *The History and Practice of Ancient Astronomy* (New York: Oxford University Press, 1998). For the most technical sections, I have consulted Neugebauer, *A History of Ancient Mathematical Astronomy* (New York: Springer-Verlag, 1975) (subsequently referred to as *HAMA*); and Pedersen, *A Survey of the "Almagest"* (Denmark: Odense University Press, 1974).

[2] Sachiko Kusukawa, *The Transformation of Natural Philosophy: The Case of Philip Melanchthon* (Cambridge: Cambridge University Press, 1995).

The Greek Astronomical Tradition

The mathematical prediction of celestial motions did not originate with the Greeks. The Babylonians were accumulating detailed records of observations that would provide the raw material for predictive models as early as the eighth century B.C.E. Ptolemy, writing in the second century C.E., identified "the beginning of the reign of Nabonassar" (747 B.C.E.) as "the era beginning from which the ancient observations are, on the whole, preserved down to our own time."[3] Babylonian astronomers studied the motions of the planets: the seven "wanderers" of Antiquity were the five visible planets, Mercury, Venus, Mars, Jupiter, and Saturn, plus the Sun and Moon as the two luminaries. In contrast, early Greek astronomical lore centered on the fixed stars to the near exclusion of planets other than the luminaries. Hesiod's *Works and Days* (seventh century B.C.E.) provides an agricultural calendar based in part on the seasonal rising or setting of prominent stars and asterisms. Later, the signs of the zodiac joined prominent non-zodiacal stars as the basis of timekeeping.

When Greek mathematicians inspired by Mesopotamian scribes developed a more rigorous astronomy, they chose to create models consonant with the cosmology already established by philosophers. Plato (427-347 B.C.E.) wrote three dialogues allowing us to reconstruct his natural philosophy: the *Timaeus*, the *Republic*, and the *Epinomis*. They describe a cosmos comprising a central sphere of earth surrounded by spheres of the other three elements, water, air, and fire.[4] Beyond them all lies the celestial realm. The

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[3] Ptolemy, *Almagest*, transl. G. J. Toomer (New York: Springer-Verlag, 1984), 3.7, p. 166. (Subsequently abbreviated as *Almagest*.) Controversy over the exact dating of events in ancient Near Eastern history is not important to my argument; Evans, *History and Practice*, 15, dates Nabonassar's reign to 747-733 B.C.E., which I have adopted for convenience.

[4] To avoid confusion, I use the lower-case "earth" to signify a pure or nearly pure element contrasted with other elements, and the upper-case "Earth" to signify the composite globe on which humans live.

apparent irregularity of planetary motion is an illusion, according to the Greek world-view; the planets are carried around the Earth with a uniform motion by circles of soul-stuff. Plato's younger contemporary Eudoxus (ca. 400 - ca. 347 B.C.E.) attempted to reproduce all planetary motions with combinations of circular motions. To each planet he assigned a set of three or four concentric spheres, each with its own axis and period of rotation. Early followers of Eudoxus include Callippus (fourth century B.C.E.), who added two spheres each to the Sun and Moon models, and Aristotle (384-322 B.C.E.), who added unrolling spheres to prevent the motions of one planet being transferred to the next; Aristotle calculated a maximum of fifty-five celestial spheres.[5] He also refined the philosophical cosmology of Plato. His fundamental division is between the terrestrial or elementary realm and the celestial or aetherial realm. The four elements making up the terrestrial realm are characterized by constant change and by rectilinear natural motion. The celestial realm is composed of aether, the fifth element, which possesses unchanging, eternal, circular motion.

The requirements natural philosophy imposed on astronomy remained constant throughout the long life of the Greek astronomical tradition. Michael Maestlin (1550-1631), an astronomer who will be discussed further in chapter four, wrote the following cosmological outline in the twilight years of Ptolemy's influence:

> How many and what are those propositions, on which the whole of Astronomy rests as foundations, and by what things, which were asserted before, are they demonstrated?
>
> They are chiefly eight: four on the Heavens, and just as many on the Earth.
>
> 1. On the Difference of Motions in the Heavens. In the Heavens there are so many more motions than one, and thus too there are more spheres.
>
> 2. On the form of the motion of the Heavens. The motion of the Heavens is circular.
>
> 3. On the quality of the motion of the heavens. The motion of the heavens

[5] Aristotle, *Metaphysics* 12.8 is the earliest source for the Eudoxan and Callippan models.

is regular and equal.

4. On the shape of the heavens. The heavens have a spherical shape.

5. On the shape of the earth, and of water joined to it, since water cannot be separated from earth. The earth is spherical, water likewise. Next, the earth together with water constitute a single globe.

6. On the place of the Earth. The Earth is in the middle of the world.

7. On the proportion of the size of the Earth to the heavens. The Earth compared to the heavens does not have a sensible size, but is like a point or center.

8. On the motion or rather on the resting of the Earth. The Earth rests altogether immobile in its own place.[6]

Other than the last sentence of point five (some strict followers of Aristotle considered the spheres of earth and water to be separate globes), Maestlin's outline reflects the consensus of Aristotelians and Ptolemaic astronomers. His eight propositions can be found in some form in every medieval and Renaissance follower of Ptolemy. All but the last appear even in the writings of early Copernicans.

The Greeks and their successors imagined the world as a series of nested spheres resembling the layers of an onion (figure 1). In a generalized picture such as this one, each planet is assigned one sphere centered on the Earth, with no space allowed between the spheres. The fixed stars share a single sphere that invariably receives the eighth place, counting outwards from the Moon. Rival traditions placed the planets in different sequences. Several alternative arrangements will be discussed in the next chapter, but for now, the number of spheres and order of the planets is not important. This schematic

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[6] "Quot & quae sunt istae propositiones, quibus ceu fundamentis tota Astronomiae innititur, & quibus, quae antè posita sunt, demonstrantur? Sunt praecipuè octo: De Coelo quatuor, & de Terra totidem. 1. De Differentia Motuum in Coelo. In Coelo esse plures motus quàm vnicum tantùm, & inde etiam plures sphaeras. 2. De specie motus Coeli. Coeli motum esse circularem. 3. De qualitate motus coeli. Coeli motum esse regularem & aequalem. 4. De figura coeli. Coelum habere figuram sphaericam. 5. De figura Terrae, eique adiunctae Aquae, quandoquidem aqua à Terra separari non potest. Terram esse sphaericam, Aquam itidem. Item Terram vnà cum aqua constituere vnum globum. 6. De loco Terrae. Terram esse in medio mundi. 7. De proportione magnitudinis Terrae ad coelum. Terram ad coelum collatum non habere sensibilem magnitudinem, sed esse instar puncti seu centri. 8. De motu seu potiùs quiete terrae. Terram omninò immobilem in suo loco quiescere." Michael Maestlin, *Epitome astronomiae, qua brevi explicatione omnia … Jam nunc ab autore denuo diligenter recognita…* (Tübingen: Philippus Gruppenbachius, Impensis Ioannis Berneri, 1610), 41-42.

diagram does not show the details of planetary motion. For strict followers of Aristotle, such as the Averroists of the later Middle Ages, each sphere represents a set of concentric orbs centered exactly on the Earth; the planet is a spot of denser aether carried on the innermost orb.

The Eudoxan homocentric orbs proved to be unsatisfactory models of the heavens. The planets brightened and dimmed, suggesting that they approached and withdrew from the Earth, but in a homocentric system the planets always maintain the same distance. Subsequent generations of Greek mathematicians modified the models to accommodate this phenomenon. Furthermore, Eudoxus could only provide crude approximations of the motions of the planets. Hipparchus of Nicaea (ca. 190-ca. 120 B.C.E.), the last important astronomer before Ptolemy himself, was the first to insist that Greek astronomers match the accuracy of the Babylonians. Using Babylonian data, he devised accurate models of the Sun and Moon, but could not reach a similar level of precision for the five planets.[7] Ptolemy succeeded in creating a complete astronomical system that predicted the motions of all the celestial bodies. His work became the standard in technical astronomy, with the result that older, outdated works were ignored and gradually lost.

Ptolemy wrote three major works on the heavens. The *Almagest*, his best-known astronomical book, explains the derivation of the models from key observations and methods for making predictions. The *Planetary Hypotheses* uses the *Almagest* models, which are presented as two-dimensional circles, to generate a set of three-dimensional orbs (or sections of orbs) filling the heavens. This chapter focuses on the *Almagest*; the

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[7] Ptolemy mentions Hipparchus' insistence on accuracy and the limits of his work in *Almagest*, 9.2, pp. 421-422; see also Evans, *History and Practice*, 213-15.

next chapter addresses issues raised by a section of the *Planetary Hypotheses* concerned with cosmic sizes and distances. A third book, the *Tetrabiblos*, deals with astrology rather than astronomy and falls outside the scope of this work.

An understanding of celestial phenomena as the Greeks perceived them is necessary for an appreciation of Ptolemy's achievement in the *Almagest*. The entire aetherial realm revolves clockwise daily. (The designation of clockwise or counterclockwise rotation is based on conventional representations that take the viewpoint of an observer at the north celestial pole). To the observer on Earth able to see only one half of the heavens at a time, objects in the heavens appear to rise in the east and set in the west. The poles of this motion are the celestial poles and its equator is the celestial equator or equatorial. Each planet possesses its own counterclockwise motion, which the observer sees as a gradual eastward motion of the planet against the background of the fixed stars. The Sun, which completes its course in a year, appears never to deviate from its path, a great circle called the ecliptic (figure 2). The ecliptic runs through the band of twelve constellations called the zodiac. It is at a slight angle to the equatorial; determining this angle, the obliquity of the ecliptic, became an important issue in the centuries after Ptolemy. The two points at which the ecliptic crosses the equator are the equinoxes, while the two points furthest removed from the equator are the solstices. The remaining planets appear to stay close to the ecliptic but deviate from it slightly, which is called motion in latitude. The five planets (that is, all but the two luminaries) also undergo station and retrogradation: they stop and briefly reverse their motion before proceeding eastward once more.

Ptolemy generated this collection of planetary motions with a set of conceptual tools devised by his predecessors--deferent, eccentric, and epicycle--and added a new element of his own making, the equant. The deferent is the circle that carries the planet around the Earth. Although the planets can be modeled with concentric deferents combined with certain other features (a point which becomes important towards the middle of the sixteenth century), Ptolemy chose to assign them eccentric deferents with centers slightly removed from the center of the world. The Sun, the simplest model, is carried on an eccentric (figure 3). Although it actually moves at a constant speed, it appears to move most swiftly when closest to Earth (perigee) and most slowly when farthest from Earth (apogee). Consequently, the seasons are not of equal length.

Ptolemy placed the remaining planets on epicycles rather than directly on their deferents (figure 4). The epicycle is a small circle carried by the deferent and possessing its own counterclockwise rotation. Each of the five planets retrogrades when it nears the perigee of its epicycle, at which time the motion of its epicycle cancels out the motion of its deferent. As it approaches the Earth, it grows brighter. The lunar model includes an epicycle to adjust the Moon's apparent speed, causing it to quicken or slow in its course through the zodiac. Because the speed of the epicycle never exceeds the speed of the deferent, the Moon itself never retrogrades. The five planets, but not the Moon, also have equants. A line passing through the apogee and perigee also passes through the Earth, the eccenter, and the equant point; the eccenter bisects the line segment between Earth and equant point. The center of the epicycle moves on the deferent at uniform speed with respect to the equant point, which means that it does not move uniformly with respect to its geometric center. Many later commentators objected to the equant on the grounds that it violated Aristotelian physics by requiring the planet to change its speed on the deferent.

Some Islamic astronomers devised alternatives to equant motion, but in Latin astronomy it was retained it in order to preserve predictive accuracy. The models for Mercury and the Moon possess additional complications that I shall not discuss here.

The Status of Astronomy

Since the time of ancient Greek and Roman civilization, the gathering of diverse branches of knowledge under the rubric of mathematics had been a standard practice. Early Pythagoreans granted mathematics, which they divided into four branches, a privileged epistemological status. Two of the mathematical branches, arithmetic and geometry, were theoretical; the other two, music and astronomy, derived from the application of theory to nature. Plato, who was heavily influenced by Pythagorean thought, adopted and passed on the fourfold division.[8] Mathematics was later incorporated into the liberal arts, the basis of education for free citizens in Antiquity. The number of liberal arts varied but eventually became codified as seven: the *quadrivium* (the four mathematical arts) plus the *trivium* of logic, grammar, and rhetoric. Through the efforts of handbook writers such as Martianus Capella (fl. ca. 365-440 C.E.) and especially Boethius (ca. 480-524/25) the ideal of the liberal arts was transmitted to scholars of the Middle Ages. Handbooks preserved a little of the content of the liberal arts; just as importantly, they provided the concept of the *quadrivium* as an organizing structure for the knowledge that was to be recovered in the twelfth and thirteenth centuries.

The astronomy of the Latin handbooks and encyclopedias available to the early Middle Ages was rudimentary in comparison to the *Almagest* and unsuitable for exact prediction. Such books present a cosmology similar to the eight propositions of astronomy listed by Maestlin, along with basic geography, the circles of the celestial

[8] Walter Burkert, *Lore and Science in Ancient Pythagoreanism*, transl. Edwin L. Minar, Jr. (Cambridge: Harvard University Press, 1972), is a classic study of the Pythagoreans. For the influence of the Pythagoreans on Plato, see Peter Kingsley, *Ancient Philosophy, Mystery, and Magic: Empedocles and Pythagorean Tradition* (Oxford: Clarendon Press, 1995).

sphere (including the equatorial and ecliptic), and the constellations. They also provide some information about the planets, typically including a list of Greek names and their Latin meanings, the order of the planets and perhaps their distance from the Earth. Most assign approximate periods to the planets: thirty years for Saturn; twelve for Jupiter; two for Mars; one year for the Sun, Venus, and Mercury; and a month for the Moon. Retrogradation is described but not explained. Though some authors understood that eccentric deferents cause unequal apparent motion, it is doubtful whether they knew that Ptolemy used epicycles to explain retrogradation, since epicycles are not mentioned in early medieval astronomical texts. A limited predictive astronomy appears in the *computus* tradition of time-reckoning, developed by Christians to construct a calendar based on the motions of the Sun and Moon. In the hands of scholars like Bede (672/3-735) *computus* provided an entry into a Christian study of the heavens and their motions.[9]

The universities that began to appear in the late twelfth and thirteenth centuries organized the arts curriculum around the liberal arts and the three philosophies--natural, moral, and metaphysical.[10] Hence, mathematics was included in the general revival of knowledge. In practice it extended beyond the strict limits implied by the *quadrivium*, since arithmetic and geometry could be applied to many aspects of nature (figure 13). Thomas Aquinas (1225-1274) introduced the designation of applied mathematics collectively as "middle sciences," a category also referred to in the Renaissance as

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[9] The Latin handbook tradition is described in William H. Stahl, *Roman Science: Origins, Development and Influence to the Later Middle Ages* (Madison: University of Wisconsin Press, 1962). For a survey of medieval Latin astronomy to the thirteenth century, see Stephen McCluskey, *Astronomies and Cultures in Early Medieval Europe* (Cambridge: Cambridge University Press, 1998). For a partial history of *computus* see the translator's introduction in *Bede: The Reckoning of Time*, transl. Faith Wallis (Liverpool: Liverpool University Press, 1999).

[10] For an introduction to medieval universities, see *A History of the University in Europe*, ed. Hilde de Ridder-Symoens, vol. 1, *Universities in the Middle Ages* (Cambridge: Cambridge University Press, 1992).

"mixed sciences."[11] In the early modern period two additional sciences made regular appearances in mathematical studies. Geography, a branch of applied mathematics not on the original list, became important in the fifteenth century with the rediscovery of Ptolemy's *Geography*. Cosmography, the study of the cosmos, came to occupy an important place in early-modern writings. It included the mathematical subjects of astronomy, geography, and navigation, but also the distinctly un-mathematical study of natural history.[12]

Astronomy was perhaps the most esteemed art of the *quadrivium*; as a branch of mathematics, however, astronomy was not synonymous with all aspects of the study of the heavens. Aristotelian thought dominated the arts curriculum of the universities, and much of intellectual life in Europe, from the thirteenth through the sixteenth centuries. In his hierarchy of knowledge, Aristotle carefully distinguished between physics (or natural philosophy) and mathematics. Physics, the study of motion and change, dealt with all the qualities of matter, such as heat and cold or heaviness and lightness.[13] Mathematics separated number from other qualities of matter, though astronomy and other mixed mathematics dealt with the physical manifestations of mathematical concepts. In general, causal explanations of the sort Aristotle preferred were associated more with physics than

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[11] W. R. Laird, "Mixed Sciences," in *Encyclopedia of the Scientific Revolution from Copernicus to Newton*, ed. Wilbur Applebaum (New York: Garland, 2000), 439.

[12] For an overview of cosmography, see David C. Goodman, *Power and Penury: Government, Technology and Science in Philip II's Spain* (Cambridge: Cambridge University Press, 1988), chapter 2, "Cosmography and the Crown," 50-87.

[13] Some modern historians use the term "cosmology" interchangeably with "physics" to signify the natural-philosophical study of the heavens, as opposed to mathematical astronomy, but others use it to describe concerns shared by physics and astronomy. "Cosmology" does not appear in medieval or Renaissance Latin texts; Edward Grant, *Planets, Stars, and Orbs: The Medieval Cosmos, 1200-1687* (Cambridge: Cambridge University Press, 1994), 7.

with astronomy.[14]

A simplified interpretation of the history of astronomy based on the work of pioneer historian of science Pierre Duhem, still to be found in some studies, applies the categories of realism and instrumentalism (or fictionalism) to the entire scope of Aristotelian and Ptolemaic thought. According to this view, physics is realist--that is to say, it seeks to describe reality--while astronomy is instrumentalist--it makes no claim that its mathematical models relate to reality in any way. The actual relationship between the two disciplines was one of complicated interdependence (allowing, of course, for change over time and variation between individuals).[15] The *locus classicus* for historians of science attempting to differentiate between astronomy and cosmology appears in the commentary on Aristotle's *Physics* by Simplicius (6th century C.E.), who quotes an explanation of the distinction given in a summary of Posidonius by Geminus of Rhodes:

> It is the task of physical speculation to inquire into the nature of the heaven and the stars, their power and quality, their origin and destruction; and, indeed, it can even make demonstrations concerning their size, form, and arrangement. Astronomy does not attempt to speak of any such thing but demonstrates the arrangement of the heaven, presenting the heaven as an orderly whole, and speaks of the shapes, sizes, and distances of the Earth, Sun, and Moon, of eclipses and conjunctions of the stars, and of the quality and quantity of their motions. Therefore, since it deals with the investigation into quantity, magnitude and

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[14] For partial explanations of physics and mathematics see Aristotle, *Physics* 2.2 and *Metaphysics* 11.3. Aristotle's doctrine of causes appears in *Physics* 2.3. As I argue in chapter 4, certain types of causation could be construed as suitable to astronomy.

[15] Pierre Duhem, *ΣΩΖΕΙΝ ΤΑ ΑΙΝΟΜΕΝΑ: Essai sur la notion de théorie physique de Platon a Galilée* (Paris: Hermann et Fils, 1908); English translation, *To Save the Phenomena: An Essay of the Idea of Physical Theory from Plato to Galileo*, transl. Edmund Dolland and Chaninah Maschler (Chicago: University of Chicago Press, 1969). Duhem's own characterization of the history of astronomy is considerably more nuanced than the abbreviated form in which it has been adopted by some later historians. Two recent monographs with subject matter overlapping this dissertation use the instrumentalist/realist categories as a basis for analysis: Anna Marie E. Roos, *Luminaries in the Natural World: The Sun and the Moon in England, 1400-1720* (New York: Peter Lang, 2001), begins with an extreme version based on a superficial reading of Grant's *Planets, Stars, Orbs*; and Kenneth Howell, *God's Two Books: Copernican Cosmology and Biblical Interpretation in Early Modern Society* (Notre Dame: University of Notre Dame Press, 2002), follows a modified and more plausible version.

> quality in relation to form, naturally it needed arithmetic and geometry. . . . [T]he astronomer, when he makes demonstrations from external circumstances, is not competent to perceive the cause, as when, for example, he makes the Earth and the stars spherical. . . . But he must take from the physicist the first principles, that the motions of the stars are simple, uniform, and orderly, from which he will demonstrate that the motions of them all are circular. . . .[16]

With caution, we can use Geminus' explanation to provide a partial description of the goals of each science. Through mathematics, astronomy determines the motions, sizes, and distances of the planets and stars, and of the systems of orbs that carry them. Physics or cosmology provides the "first principles" from which the astronomer proceeds; for example, it alone establishes that the planets and stars are carried on orbs moving with uniform circular motion. The astronomer is limited to determining which combination of orbs can produce the motions of a given planet. Astronomy must operate in accord with physics because astronomical models should reflect physical reality. The determination of "shapes, sizes, and distances of the Earth, Sun, and Moon," and of the planets and stars, becomes meaningless if the astronomer bases his calculations on imaginary models.[17]

The subordination of mathematical astronomy to causal physics, though widely accepted, did not meet with universal acceptance in Antiquity (or any other time). More significant to our story is the identification of mathematics and physics as separate spheres of knowledge, both of which contribute in meaningful ways to our understanding of the heavens. Aristotle began his exposition of Eudoxan astronomy by acknowledging that mathematics is indispensable in investigating the number of movers. Pliny (ca. 23-79

[16] Translated in Evans, *History and Practice*, 218-19.

[17] Criticisms of the "instrumentalist" approach to astronomy generally supportive of my reading of the physics/astronomy distinction include G. E. R. Lloyd, "Saving the Appearances," *Classical Quarterly* 28 (1978): 202-222; and Peter Barker and Bernard R. Goldstein, "Realism and Instrumentalism in Sixteenth Century Astronomy: A Reappraisal," *Perspectives on Science* 6 (1998): 232-58.

C.E.) refers to the attempts of mathematicians to measure the divine and unimaginably large cosmos. While he considered such attempts to verge on blasphemy, his attack testifies that determining the sizes and distances of celestial bodies had become a recognized aspect of mathematics.[18] Cicero (106-43 B.C.E.) regarded their efforts with greater approval:

> For the system of the mathematicians, which should have been known by those people [*Chaldaei*, perhaps astrologers in general], teaches how low the Moon, nearly touching the Earth, is carried; how distant it is from the star of Mercury, the nearest, how much further moreover from [the star] of Venus; then by what space it is distant from the Sun, by the light of which it is thought to be illuminated. Truly the remaining three distances are infinite and immeasurable: from the Sun to the star of Mars, thence to that of Jupiter, from it to that of Saturn, from there to that heaven which is the outermost and last of the world [i.e., the sphere of fixed stars].[19]

Cicero contrasts the authentic knowledge of mathematics with the worthless predictions of astrology, putting them in the same relationship as true physics and superstitious augury. Despite its limits, mathematics could provide meaningful information about how the heavens were arranged. Cicero's skeptical attitude towards divination is anomalous with his Stoic tendencies—astrology being accepted by most Stoics—but he followed established ideas about the role of mathematics.

Geminus should not be followed slavishly by historians. His influence on astronomy during the medieval and early modern periods has not been studied and may have been minor. Of particular concern is the fact that the work quoted above was

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[18] Aristotle, *Metaphysics*, 12.8; Pliny, *Natural History* 2.1.

[19] "Docet enim ratio mathematicorum, quam istis notam esse oportebat, quanta humilitate luna feratur terram paene contingens, quantum absit a proxima Mercuri stella, multo autem longius a Veneris, deinde alio intervallo distet a sole, cuius lumine collustrari putatur. Reliquo vero tria intervalla infinita et immensa, a sole ad Martis, inde ad Iovis, ab eo ad Saturni stellam, inde ad caelum ipsum, quod extremeum atque ultimum mundi est." Cicero, *De Senectute, De Amicitia, De Divinatione*, Loeb Classical Library, 2.43, pp. 472-474 (my translation). Cicero also includes comparing the sizes of the Sun and Earth among the tasks of mathematicians in *De Divinatione* 2.3, p. 380.

unavailable in medieval Europe, even though scholastics had a general notion of the disciplinary division.[20] Astronomical works occasionally strayed into physics, digressions that could be interpreted as the mathematician looking to the physicist for first principles, as in Maestlin's eight propositions (quoted on page 5 above). In the *Almagest*, Ptolemy presents arguments for the sphericity of the heavens drawing on simple geometry as well as "physical considerations" involving the nature of aether and earth.[21] The appearance of occasional references to physical arguments, therefore, must not be construed automatically as flouting the distinction.

Astronomy also overlapped with astrology, which used astronomical data to make its own predictions. A strict Aristotelian would have considered astrology as the study of celestial effects on the lower realm to be a branch of physics. By the middle of the sixteenth century, ideas about the proper subject matter of astronomy and its relationship to other types of knowledge were changing. Nevertheless, it is generally true that a work of astronomy deals with the mathematical treatment of the subjects named by Geminus. The main authority for mathematical astronomy was Ptolemy, though few read his work directly; most people only encountered Ptolemaic astronomy through the intermediary of textbooks.

[20] Grant, *Planets, Stars, and Orbs*, 36, n. 67. Grant begins his discussion of medieval cosmology with the quotation nonetheless. A less specific version of the distinction became available in the later Middle Ages with the translation of Simplicius' commentary on *On the Heavens*.

[21] *Almagest*, 2.3, pp. 38-40.

The Textbook Traditions: *Sphaera* and *Theorica*

Medieval manuscripts attest the enduring popularity at universities of certain astronomical textbooks. The core texts included three books by John of Sacrobosco (fl. ca. 1221-ca. 1244): the *Algorismus*, the *Computus*, and the *Tractatus de sphaera*. These three works often survive bound together with other astronomical texts, including the Alfonsine Tables or other astronomical tables with canons (instructions for use), as well as, from the late thirteenth century on, a *theorica planetarum*.[22] Gradually the study of astronomy came to be identified with the reading of a *sphaera* and a *theorica* as the basic and advanced treatises. Many early printed books of astronomy included a *sphaera* (usually that of Sacrobosco) and a *theorica*.[23] Some university statutes stipulated a course of study including a *sphaera* for the bachelor of arts and a *theorica* for the master of arts, a pattern that appears at Oxford and Vienna in the fifteenth century and Wittenberg in the sixteenth century.[24] These two genres of textbook are central to this study because of their unusual longevity and influence.

Virtually no evidence has survived concerning the life of John of Sacrobosco.[25] He is considered to be English by some medieval sources and most modern scholars,

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[22] For a survey of the medieval manuscript evidence see Olaf Pedersen, "The *Corpus astronomicum* and the Traditions of Mediaeval Latin Astronomy: A Tentative Interpretation," *Colloquia Copernicana III: Astronomy of Copernicus & Its Background*, Studia Copernicana 13 (Wrocław: Ossolineum, 1975), 57-96.

[23] Numerous examples are catalogued in Joseph Jérôme de Lalande, *Bibliographie astronomique, avec L'histoire de l'astronomie depuis 1781 jusqu'a 1802* (Paris: de la Republique, 1803).

[24] For the requirement at Oxford see Hastings Rashdall, *The Universities of Europe in the Middle Ages*, ed. F. M. Powicke and A. B. Emden (London: Oxford University Press, 1936, 1969), 3:254-55; for Vienna see Claudia Kren, "Astronomical Teaching at the Late Medieval University of Vienna," *History of Universities* 3 (1983): 15-30. The Wittenberg statutes are discussed later in this chapter.

[25] On Sacrobosco see Olaf Pedersen, "In Quest of Sacrobosco," *Journal for the History of Astronomy* 16 (1985), 175-221; and Lynn Thorndike, *The "Sphere" of Sacrobosco and Its Commentators* (Chicago: University of Chicago Press, 1949). Scholarly writing on Sacrobosco uses Latin and English forms of his name indifferently, along with the more dubious "Halifax."

though the suggestion that he was Scottish cannot entirely be discounted. His surname, meaning "Holywood," may reflect a birthplace or family name. Sacrobosco probably attended the University of Oxford; around 1221 he moved to Paris where he lectured on the *quadrivium*. His book on time-reckoning, the *Computus*, ends with a verse quotation from Boethius and a few additional lines added by an unknown person that are believed to commemorate Sacrobosco's death. One crucial line gives the date: "In the year of Christ a thousand, twice a hundred, four times ten and four. . . ."[26] Unfortunately, the sense may be either "ten four times, and four," or "ten and four, four times," putting his death in either 1244 or 1256. His tombstone was destroyed long ago, but from descriptions we know that it was engraved with the image of an astrolabe or other astronomical instrument in honor of his fame as an astronomer, together with a short verse: "Johannes de Sacrobosco Computista, who divided times, lies here, carried away by time. You who will follow in time, be mindful that you will die. If you are grieved, weep; I beg you, pitying, pray for me!" The designation *computista* tells us that he was also well known as a practitioner of *computus*, the art of time-reckoning.[27]

Sacrobosco wrote several mathematical textbooks. The *Algorismus* explains simple arithmetical calculations using arabic numerals, a novelty introduced to the Latin West only about a hundred years previously; he may have written it as a lecture on arithmetic. The *Tractatus de sphaera*, an elementary textbook, explained astronomical

[26] "M. Christi bis C. quarto deno quarter anno. . . ." The verse is quoted in full in Thorndike, *Sphere of Sacrobosco*, 6-7 (my translation).

[27] "De Sacrobosco qui Compotista Ioannes/Tempora discrevit iacet hic a tempore raptus./Tempore qui sequeris, memor esto quod morieris./Si miser es, plora; miserans pro me, precor, ora!" Quoted in Thorndike, *Sphere*, 2 (my translation).

phenomena that depend on the daily rotation of the heavens.[28] The *Computus* earned Sacrobosco his designation as *computista*, a specialist in timekeeping and the calendar. A fourth book, the *Tractatus de quadrante*, explains the use of another astronomical instrument, a kind of quadrant called the *quadrans vetus*; its attribution to Sacrobosco is less certain. Relatively few manuscripts of the *Tractatus de quadrante* survive. The *Algorismus* enjoyed moderate popularity, in manuscript and print. The *Computus* apparently fared better, with a number of manuscripts and around thirty-five printed editions; about half were printed in Wittenberg, suggesting that the university was an important center for *computus* studies in the early modern period. Sacrobosco's most enduring work proved to be his *Sphaera*, which is known from hundreds of manuscripts as well as hundreds of printed editions.[29]

Sacrobosco's *Sphaera* exerted a great influence on the medieval and early modern textbook tradition. However, it should not be regarded as a singular work. Sixteenth-century authors thought of the *sphaera* as a type of textbook suitable for the novice student. Sacrobosco's *Sphaera* was not unique, but it held pride of place as one of the two or three most important *sphaeras*. Such is the judgment of Robert Recorde (ca. 1510-1558), author of his own book "on the sphere," *The Castle of Knowledge*. Recorde

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[28] Despite Roos, *Luminaries in the Natural World*, 15, who describes Sacrobosco's *Sphaera* as a work of cosmology with essentially no connection to the *Almagest*, it is definitely astronomical and was treated as a part of the *quadrivium* in statutes.

[29] Throughout this study, I refer to the textbook tradition generically by the Latin name of *sphaera*, to avoid confusion with other astronomical "spheres" such as the armillary sphere or the celestial spheres. Exceptions are English-language quotations referring to the genre as "spheres." In such cases, the meaning will be clear from the context. Most of the figures for manuscripts and editions come from Pedersen, "In Quest of Sacrobosco," 182 ff. Francis R. Johnson estimated that at least 30 editions of the *Sphaera* from before 1501 survived, plus at least 200 from 1501-1600, and that other editions were totally lost; "Astronomical Text-books in the Sixteenth Century," in *Science, Medicine, and History: Essays on the Evolution of Scientific Thought and Medical Practice Written in Honour of Charles Singer*, ed. E. Ashworth Underwood (London: Oxford University Press, 1953), 1:285-302.

thoughtfully gave his opinion of books on astronomy that the reader was likely to encounter, identifying many of them clearly as books on the sphere. Sacrobosco was both praised by Recorde and frequently cited by him.[30] The long sixteenth-century *sphaeras* that I shall discuss in later chapters included most or all of the topics introduced in the short medieval textbook. The major topics of the *sphaera* genre include the arrangement and size of the universe (usually including some truly cosmological or physical material); the circles of the heavens and the Earth; risings and settings; and, on occasion, rudimentary planetary astronomy.

Mathematical authors defined a *sphaera* as a book about the 24-hour rotation of the heavens around the stationary Earth called the "first motion," causing the appearance of rising and setting and as a book about the armillary sphere or *sphaera materialis*, an astronomical instrument used as a teaching tool (figure 2). Later, when Sacrobosco and other *sphaeras* came to be paired with more advanced books, the introductory works also were described as being about the first part of astronomy.[31] At the time Sacrobosco wrote, early in the thirteenth century, no second part of astronomy existed as such, so he could not have been aware that he was creating the first part. The first major examples of second part, the *theorica planetarum*, also began to appear in the thirteenth century and acquired definitions paralleling those for a *sphaera*. It became a book about the "second

[30] Robert Recorde, *The Castle of Knowledge, containing the explication of the sphere both celestiall and materiall* (London: Reginalde Wolfe, 1556), especially the list of textbooks on 98-99. See chapter 6 for further discussion of Recorde's *Castle*.

[31] For instance: "Astronomy has two parts. The former inquires into and explains the first motion, turning around the remaining orbs of the fixed and wandering stars from the East to the West, which is completed in the space of twenty-four hours." "Astronomia duas habet partes. Prior inquirit & explicat primum motum, qui ab Ortu in Occasum reliquos stellarum fixarum & errantium orbes circumagens, uigintiquatuor horarum spacio absoluitur." Caspar Peucer, *Elementa doctrinae de circulis coelestibus et primo motu, recognita et correcta* (Wittenberg: Iohannes Crato, 1569), 18 (my translation).

motion" (motions of the planets and the sphere of fixed stars contrary to the first motion) or a book about the instrument called an equatorium, as in the *Theorica planetarum* of Campanus of Novara (d. 1296), which is an instruction manual for creating and using such an instrument.[32] Maestlin, writing nearly three and a half centuries after Sacrobosco, could answer the question "How many parts of Astronomy are there?" as follows:

> Two; the former is called *Sphaera*, or doctrine of the sphere, because it considers and explains the phenomena and rules of the first motion in relation to the material sphere, as if with an image of the first motion. The other is called *Theorica planetarum*, since it scrutinizes and reckons the appearances, periods, anomalies, *et cetera*, of the second motion with Theorias of the planets as visible images of the second moveables.[33]

In this context, the "Theorias" are two-dimensional representations of planetary models that Maestlin pairs with the armillary sphere: "those instruments which we call MATERIAL SPHERE and THEORIAS PLANETARUM."[34]

The content of Sacrobosco's *Sphaera* corresponds roughly to the first two books of Ptolemy's *Almagest* together with some Aristotelian cosmology.[35] The first chapter provides students with the geometry and cosmology they need to understand the rest of

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[32] Campanus of Novara, *Campanus of Novara and Medieval Planetary Theory. Theorica Planetarum*, transl. Francis S. Benjamin, Jr., and G. J. Toomer (Madison: University of Wisconsin, 1971). Further information about *equatoria* in general can be found in *The Equatorie of the Planetis*, ed. D. J. Price with linguistic analysis by R. M. Wilson (Cambridge: Cambridge University Press, 1955).

[33] "Quot sunt partes Astronomiae? Duae, Prior appellatur Sphaera, vel doctrina sphaerica, quia in sphaera materiali, velut imagine primi mobilis, phaenomena & rationes primi motus considerat & explicat. Altera Theorica planetarum dicitur, quòd Theorijs planetarum, velut imaginibus secundorum mobilium apparentias, conuersiones, anomalias, &c. secundi motus scrutantur, & numerat." Maestlin, *Epitome astronomiae* (1610), 18-19 (my translation).

[34] "Ea enim dum multiplices & vberimos vsus instrumentorum istorum, quae SPHAERAM MATERIALEM, &, THEORIAS PLANETARVM, vocamus, explicat. . . ." Maestlin, *Epitome astronomiae* (1610), 18 (my translation).

[35] Aristotelian cosmology derives mainly from Aristotle's *Physics*, *On the Heavens*, *Meteorology*, and *Metaphysics*. For the summary of Sacrobosco's *Sphaera* that follows, I have consulted and quoted from the translation by Thorndike in *Sphere of Sacrobosco* (1949), 118-42, which is satisfactory for a general impression of the content of the text but not for an in-depth study. See Edward Rosen, review of *The "Sphere" of Sacrobosco and Its Commentators*, by Lynn Thorndike, *Isis* 40 (1949): 257-63.

the book. A brief discourse on geometrical definitions of a sphere gives way to the two divisions of the sphere, understood here as the entire celestial realm, which contains many lesser spheres. According to substance, the heavens can be divided into nine spheres: the *primum mobile* or “first moveable” (the invisible outermost sphere which imparts a daily motion to all the remaining spheres below it), the firmament or sphere of fixed stars, and the spheres of the seven planets (figure 1). Note that in this late illustration, a tenth sphere has been added to the nine identified by Sacrobosco. In western Europe, the addition of spheres beyond the fixed stars was the main alteration to predictive astronomy between Ptolemy and Copernicus. According to accident, the sphere of the heavens can be divided into *sphaera recta* and *sphaera obliqua*, meaning that it will appear different to observers at the Earth’s equator--*sphaera recta*--or elsewhere on the Earth--*sphaera obliqua* (figure 5). The Aristotelian concepts of *substance* and *accident* here signify the contrast between the true and essential division of the heavens on the one hand, and its chance appearance from a particular vantage point on the other.

The cosmos itself is divided into two parts, the *aetherial* and *elementary regions*. The aetherial region, composed entirely of the element of aether, is characterized by circular motion; it contains all the celestial spheres and begins with the sphere of the Moon. The elementary region is composed of the four remaining elements of fire, air, water, and earth, in other words the terrestrial realm; it is characterized by alteration and corruption.[36] Sacrobosco identifies two types of circular motion found in the aetherial realm. The *first motion* or 24-hour rotation is imparted by the *primum mobile*. The entire

[36] Although Sacrobosco does not state so explicitly, the elementary region is also characterized by rectilinear motion, the manifest quality of the four sublunar elements; see Aristotle, *On the Heavens* 1.2.

celestial realm participates in this motion, which proceeds from east to west. The *second motion* occurs on its own axis, slightly tilted from the axis of first motion; each planet has its own second motion which proceeds for the most part from west to east, as determined by the planet's shifting position with respect to the fixed stars. The stars, too, have their own second motion.[37]

Sacrobosco gives three "reasons" for the sphericity of the heavens which constitute physical explanations. First, a sphere is most like an archetype which has "neither end nor beginning."[38] Second, a sphere contains the most space and is most efficient. Third, any other shape would have angles, resulting in two problems: the corners would thrust outside the cosmos and be without a place, while the interstices would be vacant of bodies (figure 6). The results would contradict Aristotelian physics. For a fourth, mathematical reason, Sacrobosco cites an Islamic author, al-Farghānī (ninth century), whose introduction to astronomy had been translated into Latin: a star, such as the Sun, appears to be the same size when rising, setting, or directly overhead. But if the sky were flat, the star would be closer and appear larger when crossing the meridian. Sacrobosco also uses a combination of physical and mathematical arguments to show that both the Earth and the surface of the sea are spherical (treating the two elements as separate bodies), that the Earth is at the center of the cosmos, that it is like a point in

[37] In modern terms, the first motion is the appearance of celestial motion caused by the daily rotation of the Earth on its axis from west to east. From a heliocentric perspective, the Ptolemaic second motions actually include two kinds of motions: the appearance of motion by the planets and stars caused by the yearly revolution of the Earth around the Sun and the precession of the equinoxes, combined with the actual motion of each planet in its own orbit as it revolves around the Sun or, in the case of the Moon, around the Earth.

[38] Sacrobosco, translated in Thorndike, *Sphere of Sacrobosco*, 120.

comparison to the heavens, and that it is immobile (figures 7 and 8).[39] The chapter concludes with a procedure for the measurement of the size of the Earth devised by the classical author Eratosthenes.

The second chapter, as explained in the *proemium*, "give[s] information concerning the circles of which this material sphere [i.e., armillary sphere] is composed and that supercelestial one [i.e., the heavens], of which this is the image, is understood to be composed."[40] The text shows that Sacrobosco taught with astronomical instruments available in his classroom. The list of circles includes both great circles (the equinoctial, zodiac, ecliptic, two colures, meridian, and horizon) and small circles (the tropics of Cancer and Capricorn, and the arctic and antarctic circles). The most fundamental circles are the equinoctial circle or celestial equator, corresponding to the first motion; and the zodiac or zone of planetary motion, slightly tilted with respect to the equinoctial, corresponding to the second motion. The equinoctial and the four small circles, projected onto the Earth, define the five zones or climatic regions (figure 9). Sacrobosco follows a tradition of Greek geography according to which the torrid zone, centered on the equinoctial, and the two arctic zones, in the extreme north and south, are uninhabitable or only marginally habitable. Only the temperate zones, between the tropics and the arctic or antarctic circles, could support human life beyond the level of bare subsistence.

The third chapter discusses the risings and settings of the signs and the Sun,

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[39] Medieval Aristotelians thought of the two heavy elements as separate spheres, each with its own center. W. G. L. Randles identifies Sacrobosco as a pioneer in changing attitudes towards the relationship between earth and water which culminated in their being regarded as a single terraqueous sphere in the late Renaissance in "Classical Models of World Geography and Their Transformation Following the Discovery of America," in *Geography, Cartography and Nautical Science in the Renaissance: The Impact of the Great Discoveries* (Aldershot: Ashgate Variorum, 2000). (Volume subsequently abbreviated as *GCNS*.)

[40] Sacrobosco, translated in Thorndike, *Sphere of Sacrobosco*, 118.

including their variation over the course of the year and for observers in different parts of the Earth, from the equator to the poles. The elevation of the Sun and the corresponding behavior of shadows changes at the equator, the tropic of Cancer, and the arctic circle. The length of day at the summer solstice, the longest day, changes with latitude. Sacrobosco follows the tradition of seven *climes*, bands of latitude defined by the length of the longest day (figure 10).

The fourth and final chapter gives a terse description of Ptolemaic planetary theory. The Sun is moved on an eccentric circle through the ecliptic. The remaining planets, including the Moon, have three circles each according to Sacrobosco: an equant, an eccentric deferent, and an epicycle. The epicycle creates stations and direct and retrograde motions. Sacrobosco explains lunar and solar eclipses and concludes his book with an exclusively Christian concern, the miraculous nature of the solar eclipse at full Moon during the Passion of Christ.

Sacrobosco's *Sphaera* reflects the concerns of a *computista*. The arrangement of the world in the first chapter and the circles of the armillary sphere in the second serve mainly to illustrate how the length of the day is determined by the relative positions of Sun and Earth in the third chapter. It is tempting to speculate that the book was written in part to explain the theory behind *computus*, which Sacrobosco defined elsewhere as "the science considering periods of time from the motions of the Sun and Moon."[41] The description of Ptolemaic planetary models in the final chapter bears little connection to the rest of the text, which is a coherent account of the cosmology illustrated by the

[41] "Computus est scientia considerans tempora ex Solis & Lunae motibus, & eorum ad inuicem coaequatione distincta." Sacrobosco, *Ioannis de Sacro Busto Libellus de Sphaera. Accessit Eiusdem Autoris Computus Ecclesiasticus...* (Wittenberg: Iohannes Crato, 1550), fol. I6v (the first line of the author's *proemium*; my translation).

armillary sphere.

In the late twelfth century a new type of astronomical textbook on the second motion made its appearance. Known generically as *theorica planetarum*, these books explain planetary motions in a way that is not only more advanced but also more technically oriented than the explanation in the last chapter of Sacrobosco's *Sphaera*. However, a *theorica* presents planetary models as received fact, without explaining their derivations from observations, as did Ptolemy in the *Almagest*. By the sixteenth century, reading a *theorica* was regarded as appropriate preparation for the *Almagest*.[42] The most popular medieval *Theorica* survives in over 200 manuscripts. It was sometimes ascribed to Gerard of Cremona (ca. 1114-1187) or Gerard of Sabionetta, but it lacks attribution in many copies and I shall treat it as an anonymous work.[43] The anonymous *Theorica* explains planetary models as combinations of circles, the same approach to planetary motion Ptolemy employed in the *Almagest*. Each section gives definitions of the vocabulary associated with its subject matter; thus the section on the Sun defines the eccentric circle and the technical concepts used to calculate the apparent position of the Sun. The author of the anonymous *Theorica* did not explain the purpose of his text, but possibly he wrote it as an aid to understanding astronomical tables.[44] Another medieval

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[42] For instance, Record, *Castle* (1556), 99. Roos, *Luminaries in the Natural World*, 16, wrongly claims that the leading medieval *Theorica* was a commentary on Sacrobosco.

[43] Richard Lemay, "Gerard of Cremona," in *Dictionary of Scientific Biography*, ed. Charles Coulston Gillespie (New York: Charles Scribner's Sons, 1975), 15:189, makes a strong but not conclusive case for Gerard's authorship or influence. Pedersen, "The Origins of the 'Theorica planetarum,' " *Journal for the History of Astronomy* 12 (1981): 113-23, concludes that Gerard of Cremona was a later attribution and not the original author, arguing that all the earliest manuscripts were anonymous.

[44] For a translation see "Anonymous: The Theory of the Planets," translated with an introduction by Olaf Pedersen, in *A Source Book in Medieval Science*, ed. Edward Grant (Cambridge: Harvard University Press, 1974), 451-65. For more on the medieval *theorica* genre see also Pedersen, "Theorica: A Study in Language and Civilization," *Classica et Mediaevalia* 22 (1961): 151-66; Pedersen, "The Theorica Planetarum--Literature of the Middle Ages," *Classica et Mediaevalia* 23 (1962): 225-32; and Pedersen,

Theorica, written by Campanus of Novara (d. 1296), instructed the reader in the construction of *equatoria*, which are analog computers for calculating the planets' apparent positions. Calculations made with an equatorium were necessarily approximate, but the instrument doubled as a teaching tool by illustrating a planet's circular motions.[45] As shown above (pages 20-21), in the sixteenth century Maestlin believed that the *theorica* genre explained visual images of the planetary models much as the *sphaera* explained the armillary sphere.

A new *theorica* appeared in the fifteenth century. Georg Peurbach (1423-1461), a professor at the University of Vienna, wrote the *Theoricae novae planetarum* for his lectures on astronomy in 1454.[46] Among his students was Johannes Müller (1436-1476), better known by his Latin name of Regiomontanus, who later set up a printing press in Nuremberg devoted to scientific works. Regiomontanus printed the first edition of Peurbach's *Theoricae novae* about 1472. The *Theoricae novae* soon matched the popularity of its older rival. Frequently it was printed with Sacrobosco's *Sphaera* and Regiomontanus' polemical *Disputationes contra deliramenta Cremonensia* attacking the anonymous *Theorica planetarum*. In 1460 Peurbach began preparing a paraphrase of the *Almagest*. Regiomontanus completed the work after his teacher's death and intended to print it himself, but was prevented by his own death. The posthumous publication of the

"The 'Theorica Planetarum' and Its Progeny," in *Filosofia, scienza e astrologia nel Trecento europeo* (Padova: Il Poligrato, 1992), 53-78.

[45] For text, translation, and discussion of Campanus' *Theorica* see Campanus, *Campanus and Medieval Planetary Theory*.

[46] On Peurbach and the *Theoricae novae*, see Pedersen, "The Decline and Fall of the Theorica Planetarum: Renaissance Astronomy and the Art of Printing," in *Science and History: Studies in Honor of Edward Rosen*, Studia Copernicana 16 (Wrocław: Polish Academy of Sciences Press, 1978), 157-85; and E. J. Aiton, "Peurbach's *Theoricae novae planetarum*: A Translation with Commentary," *Osiris*, 2nd ser., 3 (1987): 5-44. I use the standard modern form of the title, but it was published under several variants.

Epytoma Joannis de Monte Regio in Almagestum Ptolemei in 1496 brought Ptolemaic astronomy in Western Europe to a new level. The *Epitome* did more than summarize the *Almagest*; it discussed medieval developments and observations and drew attention to problems in Ptolemy's models, making it an excellent reference tool for the working astronomer.[47]

Peurbach organized the *Theoricae novae* roughly according to the traditional presentation of Ptolemaic astronomy. Nine chapters cover (1) the Sun; (2) the Moon; (3) the "dragon of the Moon" governing the timing of eclipses; (4) the three superior planets Mars, Jupiter, and Saturn; (5) Venus; (6) Mercury; (7) the *passiones planetarum* (a miscellany that might be described as accidental characteristics or as astrologically significant phenomena);[48] (8) declination and latitude; and (9) the motion of the eighth sphere or sphere of fixed stars, combining precession and trepidation. Solar and lunar theory necessarily came first, according to the *Almagest*:

> For none of the phenomena associated with the [other] heavenly bodies can be completely investigated without the previous treatment of these [two]. Furthermore, we find that the subject of the sun's motion must take first place amongst these [sun and moon], since without that it would, again, be impossible to give a complete discussion of the moon's theory from start to finish.[49]

The order may have served a didactic purpose as well, since Ptolemy's solar theory is the

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[47] Regiomontanus, *Epytoma Joannis de Monte Regio in Almagestum Ptolemei* (Venice: Johannis Hamman de Landoia, 1496). The standard biography of Regiomontanus is Ernst Zinner, *Regiomontanus: His Life and Work*, transl. Ezra Brown (Amsterdam: North-Holland, 1990).

[48] Standard passions include stations and retrogradations, aspects, parallaxes, and eclipses. They are "accidental" because they result from the relative positioning of the planets and the Earth, not from inherent features of planetary motion. For instance, a planet in station appears not to move but in reality continues its circular motions unchanged. See the discussion of substantial and accidental divisions of the sphere in Sacrobosco above.

[49] *Almagest*, 3 (preface), p. 131. Bracketed words were supplied by the translator.

simplest and therefore easiest for the student to understand.[50] In the following discussion I shall limit my focus to solar theory and the motion of the eighth sphere.

Ptolemy employed an eccentric circle for the Sun in the *Almagest*. In the *Planetary Hypotheses*, he explained how to convert the geometrical models of the *Almagest* to physical structures, generalized to solid orbs or sections of orbs.[51] The eccentric orb of the Sun could be made concentric with the Earth by placing it between two asymmetrical orbs. Similar asymmetrical orbs for each planet filled the spaces between eccentrics and ensured that the cosmos remained everywhere full, without void spaces. Ptolemy's nested-orb model was known to Islamic astronomy through an Arabic translation of the *Planetary Hypotheses*, where it was incorporated into the Islamic textbook tradition called *hay'a*, such as *On the Configuration of the World* by Ibn al-Haytham (Latin Alhazen, ca. 965-1040).[52] Through Arabic works, the ideas of the *Planetary Hypotheses* were transmitted to Western astronomers, but Ptolemy's text itself was not translated into Latin and seems not to have been known to westerners. While the popular medieval *Theorica planetarum* presented only the geometrical models of the *Almagest*, its readers may have learned about their spherical equivalents from physics lectures, and they would have been aware of scholastic debates on the existence of orbs for eccentrics and epicycles. Some medieval commentaries even stated that the circles represented physical orbs. Peurbach, however, gave the orb models pride of place in his

[50] Maestlin, *Epitome astronomiae* (1610), 331-32, gives four reasons to begin with the Sun: it has the simplest model; it is the most dignified body and other motions are harmonious with it; the motions of other planets are measured by the solar year; and the beginning with the Sun has the authority of Ptolemy who put the Sun first.

[51] Ptolemy preferred sections of orbs to whole orbs; later Ptolemaic astronomers preferred whole orbs.

[52] Ibn al-Haytham, *Ibn al Haytham's "On the Configuration of the World,"* ed. and transl. Y. Tzvi Langermann (New York: Garland, 1990).

theorica; for each planet, he begins with the constituent orbs and their motions.[53]

A Ptolemaic model of the Sun requires three orbs (figure 3). The body of the Sun itself is embedded in a symmetrical orb eccentric from the center of the world, called the deferent orb of the Sun.[54] This orb carries the Sun from west to east (counterclockwise when viewed from the Northern Hemisphere) about 0;59,8° each day, sufficient to complete one revolution a year. Peurbach does not use the term, but he is referring to the *tropical year*, the time it takes the Sun to return to an equinoctial or solstitial point.[55] The two asymmetrical orbs, called the deferent orbs of the apogee of the Sun, move together to create the precession of the solar apogee.[56] The precession of the solar apogee is imparted to the orbs of the apogee by the ninth sphere, the "second moveable," as Peurbach explains in the last chapter on the eighth sphere; the orbs of the Sun naturally also share in the first motion and complete a revolution each day.

Because the deferent orb is carried about by the other two orbs, its axis and poles are moved in small circles around poles and axes of the orbs of the apogee, which pass through the center of the world and so remain in place. The Sun can be thought of as

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[53] On the scholastic question of the reality of eccentric and epicyclic orbs see Grant, *Planets, Stars, and Orbs*, 275-308. Pedersen, " 'Theorica planetarum' and Its Progeny" describes medieval *theorica* commentaries incorporating physical orbs. As a manuscript shows, Regiomontanus omitted Peurbach's clear statement of the reality of the orbs: "New theorica explaining the real disposition and motion of the spheres. . . ." "Theorica nova realem sperarum habitudinem atque motum cum terminis tabularum declarans," quoted in Aiton, "Peurbach's *Theoricae novae*," 8 n. 14 (my translation).

[54] Peurbach does not give the eccentricity of the orb. In the *Almagest* it is given as 2;29 1/2p (3.4, pp. 153-55). In other words, if the radius of the eccentric circle is set arbitrarily at 60 parts, the eccentricity is 2;29,30 parts.

[55] The *tropical year* is so named because the solstices occur when the Sun appears to reach the Tropic of Cancer (summer) and Tropic of Capricorn (winter). It is about 365 1/4 days. I discuss the problem of the length of the year in chapter three.

[56] Ptolemy himself did not attribute a precession motion to the solar apogee, only to the five planets; *Almagest*, 3.4, p. 153 and n. 46. In details of this sort, medieval planetary theory deviates from its ancient source while remaining Ptolemaic in spirit and method.

being moved uniformly in an eccentric circle in the plane of the ecliptic. The remainder of the chapter is devoted to key terms such as apogee of the Sun, perigee of the Sun, and mean motion, in a manner reminiscent of the popular medieval *Theorica*. The remaining chapters on the planets follow a similar format, but are longer because of the greater complexity of the planetary models. Like Sacrobosco, Peurbach may have accompanied the lectures on his book with a visual aid, in his case an equatorium because it resembled a cross-section of a *theorica* orb model. He may have written a set of instructions for making a set of equatoria.[57]

The last chapter of the *Theoricae novae* covers the motions of the sphere of fixed stars, incorporating both the precession model from the *Almagest* and the trepidation model from the *Alfonsine Tables*, based on the treatise *De motu octavae sphaerae* attributed to Thābit ibn-Qurra (ca. 826-901 C.E.).[58] Peurbach discusses three spheres in this chapter (equivalent to the three outer spheres in figure 1). The outermost sphere, the first moveable, causes diurnal rotation. The next sphere, the ninth sphere, creates precession of the equinoxes. Elaborating on Hipparchus, who discovered that the locations of the solstices and equinoxes gradually shifted with respect to the fixed stars, Ptolemy concluded that the points of the equinoxes were fixed and that the sphere of fixed stars slowly rotated from west to east on the axis of the ecliptic at a rate of 1° in about 100 years (completing its period in about 36,000 years).[59] Peurbach preferred the

[57] Aiton, "Peurbach's *Theoricae novae*," 9.

[58] For a translation, see Neugebauer, "Thâbit ben Qurra 'On the Solar Year' and 'On the Motion of the Eighth Sphere,'" *Proceedings of the American Philosophical Society* 106 (1962): 264-99. The model is explained in Bernard R. Goldstein, "On the Theory of Trepidation According to Thābit b. Qurra and al-Zarqāllu and Its Implications for Homocentric Planetary Theory," *Centaurus* 10 (1964): 232-47.

[59] Ptolemy, *Almagest*, 7.2-3, pp. 327-38.

rate given by the *Alfonsine Tables* of about 1;28° in 200 years (a complete period in 49,000 years).[60] As a result of precession, the place of the equnioxes appears to move into a new sign every few millenia.

While Ptolemy placed precession in the eighth sphere itself, Peurbach followed the later tradition, incorporated into the Alfonsine Tables, that explained it as a motion transmitted to the eighth sphere by the ninth. The sphere of fixed stars in the *Theoricae novae* moves instead with the motion of trepidation, also called accession and recession (*accessus et recessus*) (figure 11). Two diametrically opposed circles are inscribed on the inner surface of the ninth sphere. Their centers are the mean equinoxes, fixed points where the ecliptic of the ninth sphere crosses the celestial equator. The two circles rotate counterclockwise with a period of 7,000 years, in such a way that a point at the top of one circle corresponds to a point at the bottom of the other. These points are the beginnings of the visible constellations Aries and Libra in the eighth sphere. This motion has two important observable effects. First, the obliquity of the ecliptic of the sphere of stars alternately increases and decreases over time, which explains the observation that the obliquity was less than what Ptolemy had reported.[61] Second, the true equinox oscillates, or trepidates, along the ecliptic around the mean equinox (figure 12). I have used a diagram for the Copernican version, since illustrations of the appearance of trepidation in the heavens are extremely rare. My description, therefore, re-labels some elements of the diagram. If we imagine line AB to be the equatorial, the mean equinox is C and the true equinox (where the ecliptic crosses the equatorial) trepidates between D and E. At the

[60] Aiton, "Peurbach's *Theoricae novae*," 37 n. 119.

[61] *Almagest*, 1.12, p. 63, finds the obliquity of the ecliptic to be 23;51,20°. In the early eighth century it was measured at about 23;35° (Aiton, "Peurbach's *Theoricae novae*," 38 n. 130). I return to trepidation and the

same time, C moves uniformly along the equatorial due to precession.

obliquity of the ecliptic in chapter three.

Astronomy at Wittenberg

The first sections of this chapter dealt with the relationship of astronomy to mathematics and the presentation of astronomy in two types of mathematical textbooks represented by Sacrobosco's *Sphaera* and Peurbach's *Theoricae novae*. In the remainder of this chapter, I explore how these two books became established as the core of the astronomical curriculum at the University of Wittenberg by the mid-sixteenth century. Although the pairing of *sphaera* and *theorica* was a common pattern, as we have seen, its use in individual educational contexts was accompanied by varying attitudes to and expectations about the material. In Wittenberg, Sacrobosco's *Sphaera* and Peurbach's *Theoricae novae* became part of a new search to understand God's providential design within the context of the Reformation.

The Reformation began as a movement to reform the Catholic Church from within and purge it of corruptions; it developed into a permanent schism between Catholicism and several branches of Protestantism. Lutheranism differed from other Protestant movements in that it began in and retained close ties to the university, an established center of education and intellectual life. When Martin Luther (1483-1546) initiated the push for reform that led to a decisive split with Rome, he was teaching at the University of Wittenberg, which he and his followers gradually restructured along Lutheran lines; the university became a model for other universities in areas converted to Lutheranism. The movement to reform university education in order to create theologians with a sound understanding of Lutheran doctrine was headed by Philip Melanchthon (1497-1560), one of Luther's chief supporters.[62]

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[62] The following discussion of formative events in Melanchthon's life is based on Kusukawa, *The Transformation of Natural Philosophy: The Case of Philip Melanchthon*; and Kusukawa's editorial

Inspired by Renaissance humanists, who emphasized the return to classical sources in their original language in order to avoid the deterioration of knowledge due to medieval commentators and inferior translations, Luther called for a Christianity based on the scriptures, informed by knowledge of the languages in which they were written. An early manifestation of this humanist dimension of the Reformation was the creation at Wittenberg of chairs in Greek and Hebrew. In August 1518 the young Melanchthon was appointed to the Greek chair; he quickly joined Luther and went on to obtain a degree in theology. In his call for reform, Luther strongly attacked scholastic theology, which had failed in its task of teaching that salvation could be gained through faith alone; he attacked Aristotle as the chief authority of scholasticism, and his mistrust extended beyond the use of Aristotle in theology to include all aspects of his philosophy.

Initially Melanchthon followed Luther in rejecting philosophy, including natural philosophy, but later he came to encourage the study of nature in Lutheran universities, lecturing on topics of natural philosophy and writing textbooks and prefaces to a number of books. Kusukawa has attributed Melanchthon's changed attitude to episodes of civil disorder caused by religious radicals. The first, the Wittenberg movement, occurred in 1521-22 while he headed the reform movement during Luther's absence. Riots broke out, students stopped attending classes, and Melanchthon found himself unable to assess the validity of a trio of self-proclaimed prophets. Luther finally returned to identify the

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introduction to Melanchthon, *Orations of Philosophy and Education*, transl. Christine F. Salazar (Cambridge: Cambridge University Press, 1999), xi-xxxi. The standard biographies in English are still C. L. Manschreck, *Melanchthon: The Quiet Reformer* (New York: Abingdon Press, 1958); and Robert Stupperich, *Melanchthon*, transl. Robert H. Fischer (London: Lutterworth Press, 1966). While invaluable, these and other older studies tend to present Melanchthon as conciliatory and even timid; for a re-evaluation, see John R. Schneider, "The Hermeneutics of Commentary: Origins of Melanchthon's Integration of Dialectic and Rhetoric," in *Philip Melanchthon (1497-1560) and the Commentary*, ed. Timothy J. Wengert and M. Patrick Graham (Sheffield: Sheffield Academic Press, 1997), 20-47.

“Zwickau Prophets” as false and to restore order in Wittenberg. Melanchthon began to reconsider his calling to theology at this time, identifying himself primarily as a teacher of Greek and focusing on reform of arts education.[63]

The second episode came in the mid-1520s. The overenthusiastic reformer and itinerant preacher Thomas Müntzer joined peasant uprisings that grounded their revolutionary claims in scripture, to the horror of Luther and Melanchthon. The Peasants’ War ended in May 1525, but the reformers and princes alike remained concerned about the potential for future unrest caused by religious radicals. In 1527 Melanchthon visited Thuringia to assess the situation. He discovered that many people were frightfully ignorant of Lutheran teachings and found a number of Anabaptists. The name *Anabaptism* is applied to a number of religious groups that reject the validity of infant baptism; typically they also seek broad social change. Since Müntzer and the Zwickau Prophets had been Anabaptists, Melanchthon identified the movement with socially disruptive theology in general. He began to speak out against these people who interpreted scripture according to their own preferences (according to Melanchthon) and who were associated with civil unrest. At this point he began to view philosophy in a more positive light, distinguishing bad scholastic philosophy, which infringed upon the spiritual life properly left to theology, from good philosophy, which limited itself to the corporeal life.[64] Fear of a third episode of civil disorder came in 1531; in August of that year Melanchthon began making inquiries about the possible significance of a comet that

[63] Kusukawa, *Transformation of Natural Philosophy*, 51-58; Diarmaid MacCulloch, *The Reformation* (New York: Viking Penguin, 2004), 136 ff.

[64] Kusukawa, *Transformation of Natural Philosophy*, 62-67. For a translation of the disputation she identifies as the key sign of Melanchthon’s new attitude towards philosophy, see Melanchthon, *Orations*, 23-25.

had recently appeared in the sky. Comets had a long association with wars, disasters, and the death of princes. Melanchthon's letters show he feared the comet was a sign of impending catastrophe, not an unusual response in an age fascinated with apocalypse.[65]

About the time of his interest in the comet, Melanchthon wrote a letter to Simon Grynaeus (1491-1541), an old friend, to serve as a preface to a new edition of Sacrobosco's *Sphaera* about to be printed at Wittenberg.[66] Melanchthon's responsibility for the arts curriculum at Wittenberg included provisions for teaching astronomy as a matter of course. The letter to Grynaeus in 1531, however, signals a newfound appreciation for the study of astronomy and its application in astrology founded upon a close connection between astronomy and God's providence. Once we learn to understand the motions of the stars, he says, we can perceive the orderly nature of the world, demonstrating that it was created by an intelligence:

> [O]nly those among the philosophers who spurned astronomy were professedly ungodly; having done away with providence, they also removed the immortality of our souls. If they had reached this knowledge, they would have perceived the manifest traces of God in nature, and, having noticed them, they would have been forced to acknowledge that the universe is made and governed by a mind.[67]

A little later he identifies those who deny astronomy with Epicureanism, known in the sixteenth century for the denial of God's providence and for an immoral lifestyle:

> However, there are some Epicurean theologians who mock this entire branch of learning. Not only do they take away credibility from the prophecies, but they

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[65] Kusukawa, *Transformation of Natural Philosophy*, 124-126.

[66] For a translation of the preface see Melanchthon, *Orations*, 105-112. For an early edition of Sacrobosco with the preface see Sacrobosco, *Liber Iohannis de Sacro Busto, de Sphera. Addita est praefatio in eundem librum Philippi Melanch. ad Simonem Gryneum* (Wittenberg: Iosephus Clug, 1534). Analyses of the preface and its importance can be found in Kusukawa, *Transformation of Natural Philosophy*, 126-34; and Isabelle Pantin, "La lettre de Melanchthon à S. Grynaeus: les avatars d'une apologie de l'astrologie," in *Divination et controverse religiuese en France au XVIe siècle* (Paris: Ecole normale supérieure des jeunes filles, 1987), 85-101.

[67] Melanchthon, *Orations*, transl. Salazar, 106-107.

> also disparage knowledge of motion; let us leave them to play the fool with Epicurus. For they are in a condition such that they would need medical doctors rather than geometers. It is an obvious kind of madness to spurn the knowledge of the motions. . . .[68]

The letter to Grynaeus established an important precedent in Lutheran astronomy. From this point on, Melanchthon and his followers routinely defended the study of astronomy as proof of God's providence and as a refutation of the Epicureans.[69] The identification of Epicureans as astronomically unlearned was not arbitrary. The first book of the *Almagest* disproves strange cosmological beliefs, traditionally attributed to Epicurus and his followers, that the stars move towards infinity or are created anew each day.

Epicureanism was not a common philosophical outlook in 1531, to say the least; Melanchthon settled on it as a classical exemplar of an amoral philosophy in response to his experience in 1527, when he had seen firsthand the effects of Anabaptism in Thuringia. Already in that year, Melanchthon had juxtaposed knowledge of astronomy and knowledge of moral law in a disputation preoccupied with moral law, reflecting his reaction against civil disorder: "Just as astronomy is the knowledge of the heavenly motions, which are arranged by God, so moral philosophy is the knowledge of the works, that is, of the causes and effects that God has arranged in the mind of man."[70] As atomists, Epicureans explained the world through the random collision of atoms, leaving no room for the providence of an intelligent designer. They lacked knowledge of astronomy, just as Anabaptists lacked knowledge of moral law. Furthermore, their brand of ignorance led them into an unregulated lifestyle. In 1536, Melanchthon warned against

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[68] Melanchthon, *Orations*, transl. Salazar, 108.

[69] Barker, "Astronomy, Providence and the Lutheran Contribution to Science," in *Reading God's World: The Scientific Vocation*, ed. Angus J. L. Menuge (St. Louis: Concordia Publishing, 2004), 157-87.

[70] Melanchthon, *Orations*, transl. Salazar, 24.

"ignorant theology," lacking a proper basis in philosophy, which leads to a confused and incoherent picture. "In the meantime the wavering conscience is forsaken. And since no Furies torture the mind more violently than this doubt about religion, finally all of religion is cast aside in hatred, and their minds become impious and Epicurean."[71] Proper education in natural and moral philosophy guards equally against Anabaptists and Epicureans.

To ensure that Lutherans attending university received a proper grounding in knowledge of nature as well as of theology, Melanchthon instituted an extensive series of mathematics courses at Wittenberg and other reformed universities. The Wittenberg statutes specify the lectures to be attended by students in the arts faculty:

> And privately and publicly let the first age diligently learn Latin Grammar, Dialectic, Rhetoric and the summa of Christian doctrine. Truly, let all who are engaged in philosophical studies publicly hear these lectures in which are taught the Elements of the doctrine of celestial circles, collected from John of Sacrobosco, Arithmetic, Physics, the Second Book of Pliny, and Aristotle's Ethics. But those who wish to become candidates in the degree of philosophical master, or otherwise seek more enriched knowledge of Philosophy, let them add to the lectures--of which mention has already been made--Euclid, Theoricas planetarum, and Ptolemy's Almagest. We desire the studious not just to surround themselves with the idle shadow of erudition, but to grasp true Philosophy, and to be led properly through the arts, both because it is useful to individuals for the recognition of truth, by which life is guided, and for judging rightly; and because it is necessary for public life, which cannot do without the art of counting, and measuring, the reckoning of the year, Cosmography, the doctrine of the nature of the human body, and the beginning of medical art and the description of virtues.[72]

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[71] Melanchthon, *Orations*, transl. Salazar, 127-28. On the method and physical structure of Melanchthon's providential cosmos, see also Barker, "Astronomy, Providence and Lutheran Contribution."

[72] "Et priuatim & publice prima aetas diligenter discat Grammaticam latinam, Dialecticen, Rhetoricen & summam doctrinae Christianae, Publice vero omnes qui versantur in studijs philosophicis, audiant has praelectiones in quibus traduntur Elementa doctrinae de circulis coelestibus, collecta a Ioanne de sacro Busto, Arithmetica, Physica, Secundus liber Plinij, & Aristotelis Ethica. Illi uero qui Magisterij Philosophici gradum petituri sunt, aut alioqui locupletiorem cognitionem Philosophiae adpetunt, adiungant ad praelectiones, quarum iam mentio facta est, Eucliden, Theoricas planetarum, & magnam constructionem Ptolemei. Cupimus enim studiosos non tantum inanem eruditionis vmbram sibi circundare. Sed veram Philosophiam percipere, & ordine per artes duci, quod & singulis vtile est ad agnitionem veritatis, qua regitur vita, & ad recte iudicandum, & communi vitae necessarium est, quae non potest carere arte numerandi & metiendi anni ratione, Cosmographia, doctrina de natura corporis humani, et initijs artis

The statutes for the faculty of liberal arts at Wittenberg listed the duties of ten lecturers in languages and philosophy. Two of these lecturers were assigned the duties of teaching mathematics: "Two Mathematicians, of whom the one relates the Elements, Arithmetic, and the Sphere of John of Sacrobosco; the other Euclid, Theoricas Planetarum, and Ptolemy's Almagest."[73] The statutes mention the second book of Pliny's *Natural History*, which became popular in the Renaissance as an introductory work of natural philosophy to precede study of Aristotle. It is not assigned to a mathematician, but the title of Jacob Milich's commentary on Pliny describes him as professor of mathematics at Wittenberg, and former students referred to Pliny in their astronomical writings.[74] Melanchthon took special pride in the teaching of Pliny at Wittenberg in 1531: "In which other school is the second book of Pliny expounded as clearly as it is here?"[75]

Melanchthon encouraged Wittenberg students with an aptitude for mathematics to develop their skills. In 1536 two recent graduates, Georg Joachim Rheticus (1514-1574) and Erasmus Reinhold (1511-1553), were appointed to the chairs of Lower Mathematics and Higher Mathematics respectively when the positions coincidentally became vacant in

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Medicae & virtutum descriptione." *Academiae Witebergensis leges quae bis quotannis publice recitantur. Additae sunt et colagij Theologici & Collegij Philosophici leges* (Wittenberg: Iosephus Klug, 1546), fol. A2v-A3r.

[73] "Duo Mathematici, quorum alter Elementa, Arithmeticam, & Speram Ioannis de Sacro Busco proponat Alter Eucliden, Theoricas Planetarum & Ptolemei magnam constructionem." *Academiae Witebergensis leges*, fol. D4v-E1r.

[74] Pliny, *Liber Secundus C. Plinii De mundi historia: cum commentarijs Iacobi Milichij professoris mathematum in Schola Vitabergensi, diligenter conscriptis & recognitis, Vitaeberga anno 1537* (Halae Suouorum: ex officina Petri Brubachij, 1538). For the role of Pliny at Wittenberg, see Bruce Stansfield Eastwood, "Plinian Astronomy in the Middle Ages and Renaissance," in *Science in the Early Roman Empire: Pliny the Elder, His Sources and Influences*, ed. Roger French and Frank Greenaway (Totowa, N.J.: Barnes & Noble, 1986), 219-220.

[75] Melanchthon, *Orations*, transl. Salazar, 7.

the same year.[76] Comparison of the two sets of statutes reveals what courses each professor was expected to teach; each was responsible for a mixture of mathematical and astronomical lectures.[77]

The university statutes divide mathematical studies into two groups. One set of lectures must be attended by all students in the arts faculty; the other is mandatory only for students who wish to attain the degree of master of arts. The division of lectures corresponds exactly to the division between the two mathematical lecturers in the arts statutes. As professor of Lower Mathematics, Rheticus was responsible for teaching arithmetic and a book of elements (probably geometry), as well as Sacrobosco's *Sphaera*. Reinhold, the professor of Higher Mathematics, taught advanced geometry from Euclid, a *theorica planetarum*, and the *Almagest*. For each item we can identify a publication or lecture at Wittenberg that in most cases can be linked with either Reinhold or Rheticus. Thus, Rheticus taught a textbook in arithmetic in 1536; in the same year, Melanchthon wrote a preface for the introductory textbook *Elements of Geometry*. The *Elementa* included by the statutes in the duties of the first mathematician must be such a book, since the name of Euclid (author of the more famous *Elements*) is associated with a different course. Student notes from Rheticus' lecture on Sacrobosco's *Sphaera* and a printed edition with a preface by Rheticus confirm that he taught introductory astronomy.

[76] Melanchthon's encouragement of mathematical studies by these and other interested students is discussed in Lynn Thorndike, "The Circle of Melanchthon," in *History of Magic and Experimental Science* (New York: Columbia University Press, 1923-58), 5:378-405; and Robert S. Westman, "The Melanchthon Circle, Rheticus, and the Wittenberg Interpretation of the Copernican Theory," *Isis* 66 (1975): 164-93. I discuss the later careers of Rheticus and Reinhold in chapters four and five.

[77] My analysis of the duties of the mathematical professorships contradicts a common generalization that one was responsible for mathematics, the other for astronomy, for example Owen Gingerich, "Reinhold, Erasmus," in *Dictionary of Scientific Biography*, ed. Charles Gillispie (New York: Charles Scribner's Sons, 1970-   ) (subsequently referred to as *DSB*), 11:365 (Reinhold taught astronomy); Howell, *God's Two Books*, 241 n. 46 (Rheticus was responsible only for arithmetic and geometry, and was exceptional in adding astronomy to his repertoire).

Reinhold wrote commentaries on Peurbach's *Theoricae novae* and the first book of Ptolemy's *Almagest*. Moreover, student notes from a lecture on optics given by Reinhold show that a professor's lectures might stray from the requirements of the statutes.[78]

The preface to the arithmetic textbook taught by Rheticus has been ascribed to both Melanchthon and Rheticus. Melanchthon is known to have written essays (such as prefaces and orations) for use by his students. The style of the preface--its clarity, its phraseology, and the numerous classical allusions--argue for Melanchthon as the true author. Even if we allow that Rheticus may have written it under his mentor's influence, however, the preface reveals much about the connection between the mathematical arts at Wittenberg. Its praise of arithmetic is interrupted by a lengthy digression on the virtues of astronomy. Plato's *Phaedrus*, the author says, contrasts two kinds of souls, those with wings who are enabled to delight in the pleasures of flying through heaven, and those who have lost their wings and are dragged down by earthly pleasures. While Plato imagined that the mind flew by "heroic impulses" alone, in fact it also requires the arts to fly: "the wings of the human mind are arithmetic and geometry," by means of which the soul is lifted up to contemplation of heavenly things. Epicurus and Lucretius, on the other hand, imagined ignorantly that the Sun and other celestial bodies were set afire by their motion through the sky and that stars and planets moved about in pursuit of food. "Consequently, among the philosophers only the Epicureans were ungodly, because they

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[78] Prefaces for the arithmetic and geometry textbooks are translated in Melanchthon, *Orations*, 90-104. Rheticus' preface to Sacrobosco is discussed in Edward Rosen, "Rheticus as Editor of Sacrobosco," in *For Dirk Struik: Scientific, Historical, and Political Essays in Honor of Dirk J. Struik*, ed. R. S. Cohen, J. J. Stachel, and M. W. Wartofsky, Boston Studies in the Philosophy of Science 15 (Dordrecht: D. Reidel, 1974), 245-48. For more on Rheticus' career, see Karl Heinz Burmeister, *Georg Joachim Rhetikus, 1514-1574: Eine Bio-Bibliographie*, 3 volumes (Wiesbaden: Pressler-Verlag, 1967-68). For text, translation, and discussion of the manuscript of Reinhold's lectures, see Darcy A. Lefevre, "*Demonstratio Halonis*: A Manuscript Preserving Two Sets of Student Notes from a Lecture by Erasmus Reinhold at the University of Wittenberg" (M.A. thesis, University of Oklahoma, 2002).

did not want to behold these illustrious proofs of God, that is, the most firm laws of movements and this wonderful harmony."[79] Introductory mathematics mattered because it led to knowledge of God's providence in the celestial realm.

Sacrobosco's *Computus* must have had a place at Wittenberg not recorded in the statutes, for Melanchthon saw fit to grace it with a preface addressed to Achilles Gasser in 1538 (translated in appendix 1). In the preface, Melanchthon attributes to Rheticus the current place of the *Computus* in the Wittenberg astronomical curriculum: "I greatly approve of Georg Ioachim Rheticus' plan, which attached, to the little book on the Sphere, the reckoning of the year written by the same author Iohannes de Sacro Busto."[80] His classical example for the importance of *computus* is Julius Caesar's reform of the calendar, which rationalized the different ethnic calendars and simultaneously restored the calendar to its proper relationship with the equinox. The calendar is vital to both civil and ecclesiastical matters, especially religious history. What is more, the reckoning of time requires understanding of the motions of Sun and Moon, making it an apt introduction to the study of astronomy.

The scholar who has mastered the doctrine of celestial motions can predict important events, including storms and the effects of conjunctions. However, Melanchthon values pure astronomy over astrology, calling it divinatory (*mantike*) and even prophetic because:

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[79] Melanchthon, *Orations*, transl. Salazar, 93-94.

[80] Melanchthon *Corpus Reformatorum Philippi Melanthonis Opera quae supersunt omnia*, ed Carolus Gottlieb Bretschneider, 28 vols. (Frankfurt am Main: Minerva, 1834-1900; reprint, New York: Johnson Reprint, 1963-1964), 3:575, no. 1715. (Subsequent references to this set abbreviated as *CR*.) In light of the long tradition of studying both of Sacrobosco's books in the *quadrivium*, it is difficult to ascertain exactly what Melanchthon had in mind. Perhaps Rheticus was the first at Wittenberg to approach the *Computus* from an astronomical angle, or perhaps he combined both texts in a single course.

> it gives evidence that an eternal mind is artisan and governor of the world, and that we are formed for knowledge of God and for immortality. . . . it is more prophetic to strengthen minds by means of the revealed, most certain laws of motions, so that truly they may establish that there is a God who sets in order, who governs these motions, who wishes to be known by men, for the sake of the advantage of whom he put together these varieties of motions; so much the more, when he invites us to knowledge of himself, he promises rewards for the good and punishments for the impious.[81]

Throughout the preface, the phrases "science of motions" (*scientia motuum*) and "doctrine of motions" (*doctrina motuum*) appear as synonyms for astronomy. Latin writers began to distinguish clearly between astronomy and astrology as a result of the translation movement. Following Arabic models, they divided *scientia stellarum* into *scientia motus* (or *motuum*) and *scientia iudiciorum*. The division was still current in the sixteenth century; Recorde contrasts "the Iudicial part of Astronomy" with "this parte of the motions" in the *Castle of Knowledge*.[82]

In a recent dissertation on Rheticus, Jesse Kraai uses the preface to Gasser to argue that Melanchthon and Rheticus were astrological determinists. According to Kraai, the preface identifies astronomy with astrology; by 1538, astronomy no longer existed as a separate area of thought at Wittenberg. The conclusion appears to rest on Melanchthon's affirmation that astronomy (the "doctrine of motions"), like astrology, is *mantike*, a form of divination or foretelling. By forging an identification, he hoped to shield astrology from attack by the ignorant.[83] But the text of the preface does not support the conclusion. The *mantike* of astronomy is the existence of God and the immortality of

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[81] *CR* 3:575.

[82] Richard Lemay, "The Teaching of Astronomy in Medieval Universities, Principally at Paris in the Fourteenth Century." *Manuscripta* 20 (1976): 198; Recorde, *Castle* (1556), fol. a5r.

[83] Jesse Kraai, "Rheticus' Heliocentric Providence: A Study Concerning Astrology, Astronomy of the Sixteenth Century" (Ph.D. diss., University of Heidelberg, 2003, accessed March 4, 2005); available from http://www.ub.uni-heidelberg.de/archiv/3254; see esp. 88-89.

the soul. In the oration *On Astronomy and Geography* (1536), which like the arithmetic preface was presented by Rheticus but probably written by Melanchthon, the nature of the *mantike* of astronomy is explained: "For these laws of motions are evidence that the world has not originated by chance, but that it was created by an eternal mind, and that this creator cares about human nature."[84] Both astronomy and astrology are God-given arts, but their identities are not merged. Furthermore, it is improbable that Melanchthon, a skilled rhetorician, would seek to protect astrology by associating it with astronomy. To the contrary, he states that astronomy has been exposed to attack because of its association with divination, which in this context refers to astrology. For Melanchthon, the doctrine of *computus* demonstrates God's providence because He created complicated yet predictable celestial motions to furnish us with a calendar for the proper conduct of civil affairs and church festivals. By 1550 the textbook at Wittenberg combined Sacrobosco's *Sphaera* and *Computus* in a single volume.[85]

[84] Melanchthon, *Orations*, transl. Salazar, 118.

[85] Sacrobosco, *Libellus de Sphaera. Accessit Eiusdem Autoris Computus Ecclesiasticus* (1550).

Conclusions

After a long period of time during which Ptolemy was little more than a respected name in the West, the translation movement of the twelfth and thirteenth centuries re-established his place as the pre-eminent astronomical authority. Concurrent with the recovery of Ptolemy we saw the composition of new books to provide an introduction to Ptolemaic astronomy at the universities. Many of these books fell into the two classes of *sphaera* and *theorica*. The mere act of translating the *Almagest* did not suffice, however, to elevate the general level of astronomical knowledge in Latin Europe to the heights reached by the most famous astronomers of Antiquity. Recovery was an ongoing process; the *theorica* genre, for example, became more sophisticated over time. In the first half of the sixteenth century, the *Almagest* was not only widely available; it was also understood by a critical mass of skilled readers who, like Regiomontanus, were beginning to point out its shortcomings.

The natural philosophical disciplines had a low profile at Wittenberg prior to the events of the Radical Reformation. Faced with the prospect of civil disorder and heresy, Melanchthon arrived at the strategy of reinforcing the arts curriculum. One of his hopes was that by learning about the workings of the natural world, students would come to marvel at God's providence and be led to accept His authority in other areas of knowledge, including ethics. Astronomy became a model science at Wittenberg, not because it dealt with an inherently superior subject matter (which would have contradicted Aristotelianism), but because it demonstrated the operation of an intelligent creator so clearly. His *Computus* preface is a case in point. God's providential care for humanity can be seen in the practical benefits deriving from the arts time-reckoning and astronomy. These arts allow us to predict the weather and regulate our lives. They also aid us in our study of religion by charting the course of religious history. Most important, however, they strengthen mortal faith in God's existence and benevolence.

After discovering signs of providence in the study of celestial motions, Melanchthon turned the recently founded University of Wittenberg into a center of mathematical education. The next two chapters examine some of the long-term results of the rediscovery of Ptolemy. Chapter three considers the work of Copernicus, who was among the first beneficiaries of the efforts of Peurbach and Regiomontanus. Chapter four returns to Wittenberg to look at the reaction to Copernicus among Melanchthon's students.

CHAPTER 3

ORIGINS OF COPERNICAN ASTRONOMY

The first tentative reforms of mathematics education instituted by Melanchthon in the 1530s acquired an unforeseen dimension when Rheticus, one of his mathematical protégés, visited an obscure astronomer, Nicolaus Copernicus (1473-1543), and helped set in motion the chain of events leading to the publication of *De revolutionibus orbium coelestium*.[1] Copernicus had worked on his book a long time, having conceived the idea of a Sun-centered astronomy sometime before 1514. Over the next three decades, during the first generation of reform, he developed a complete astronomical system with heliocentrism as its centerpiece. Possibly this was the first time anyone had done so, for there is nothing to tell us whether the Greek heliocentrist Aristarchus of Samos (ca. 310-230 B.C.E.) fully understood the consequences of his system or made it the basis for astronomical prediction.[2]

This chapter considers the astronomical work of Copernicus himself as a necessary prelude to understanding its reception among astronomers of the sixteenth and

[1] Nicolaus Copernicus, *De revolutionibus orbium coelestium, Libri VI* (Nuremberg: Ioh. Petreius, 1543). (Subsequently referred to as *De rev*. (1543).) Every English translation of the complete book suffers from some serious defect that limits its usefulness for scholarly work. Toomer, "Copernicus in Translation," *JHA* 12 (1981): 198-204, is a lengthy (and highly critical) review of the translation most commonly cited, that of Rosen.

[2] Modern scholars sometimes employ the terms "heliostatic" or "geokinetic" for Copernican cosmology. I shall use the more general term "heliocentric" to designate any cosmology that places the Sun at or near the center of planetary (including terrestrial) motion, in contrast to "geocentric" systems in which the Earth is at or near the center of planetary motions. On Aristarchus, see Thomas Heath, *Aristarchus of Samos: The*

early seventeenth centuries. Copernicus adopted a Sun-centered cosmology roughly three decades before the publication of *De revolutionibus* but did not record his reasons for doing so. Determining the true ordering of the planets appears to have been one element in the search that led him to heliocentrism; therefore, I discuss the problem of the planets' order in ancient Greek astronomy and philosophy. Three rival geocentric cosmologies were supported by an array of rationales. Finding the distances to celestial objects, a traditional part of mathematics, depended in part on one's chosen cosmology. For Copernicus, heliocentrism may have been a creative solution to the problem, invoking the principle of relating a planet's position in the cosmos to its period of revolution.

The bulk of the chapter moves beyond cosmological problems to a semi-technical summary of the planetary models of *De revolutionibus*. Because a heliocentric model can be converted to a geocentric one, identifying an author's reliance on Copernicus (or lack of it) requires that we move beyond a simple search for assertions that the Earth moves and the Sun is at rest. It requires understanding the elements of a planetary model and how they combine to create the composite motions that observers can see in the heavens. It requires careful examination of the values assigned to the different motions, since a small difference in some key value may tell us whether a given author based his model on Ptolemaic or Copernican parameters.

I have chosen theories of the Sun's motion as the main subject of my study for reasons that have nothing to do with the physical centrality of the Sun in Copernicanism or the mystical significance of the Sun in Renaissance revivals of Hermeticism and Pythagoreanism, often alleged to be a major factor in the early adoption of

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Ancient Copernicus. A History of Greek Astronomy to Aristarchus together with Aristarchus's Treatise on the Sizes and Distances of the Sun and the Moon (Oxford: Clarendon Press, 1913).

heliocentrism.[3] For quite practical reasons, astronomical texts dealing with planetary astronomy open with the Sun, and therefore solar models are potientially the most likely to be studied and modified.[4] The Sun is the most important celestial object in nautical astronomy, an important application of astronomy in early modern England discussed in chapters five and six. My discussion of the remaining planetary models in *De revolutionibus* is considerably abbreviated, as they play a subsidiary role in my analysis.

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[3] The classic study of Hermetic mysticism in early Copernicanism is Francis A. Yates, *Giordano Bruno and the Hermetic Tradition* (Chicago: University of Chicago Press, 1964).

[4] For example, Reinhold's commentary on the *Theoricae novae*, to be discussed in the next chapter. Exceptions exist, such as Giovanni Antonio Magini, *Novae coelestium orbium theoricae congruentes cum observationibus N. Copernici* (Venice: Damianus Zenarius, 1589), which I discuss briefly in chapter 7. Magini (1555-1617) makes a geocentric conversion of Copernican models that begins with the outermost sphere and works inward to the Earth. His order of treatment would make less sense in a true Copernican work, since the motions of the Earth determine the appearances of the other planets.

Nicolaus Copernicus

Copernicus was born in Thorn on February 19, 1473.[5] After the death of his father about 1485, he was looked after by his uncle Lucas Watzenrode, who became the Bishop of Ermland in 1489. From 1491 to 1495 Copernicus attended the University of Cracow. In 1496 he moved to Italy, where he attended several universities, receiving a degree in canon law from the University of Ferrara in 1503. He then returned to Ermland, serving as his uncle's physician and assistant for several years. In 1510 he moved to Frauenberg, where he remained a canon of the Church until his death in 1543.

On May 1, 1514, Matthew of Miechow, a physician in Cracow, entered an unusual item in his library catalogue: "Next a six folio Theorica maintaining that the Earth is moved, the Sun truly is at rest."[6] Despite the anonymity of the entry, there can be no question that Copernicus was the author. Matthew's catalogue gives us a *terminus ad quem* for the writing of the work known as the *Commentariolus*, which Copernicus probably began sometime after his return from Italy in 1503. The *Commentariolus* is a bare description of the combinations of circular motions for each planet in a heliocentric system envisioned by Copernicus (figure 14). As is characteristic of a *theorica*, it lacks observations or derivations. At this stage, Copernicus believed that working out the

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[5] The best recent account of Copernicus' life is N. M. Swerdlow and O. Neugebauer, *Mathematical Astronomy in Copernicus's "De revolutionibus"* (New York: Springer-Verlag, 1984), 3-89. Most biographies of Copernicus are derivative or otherwise add little to our understanding; for an annotated bibliography see Rosen, *Three Copernican Treatises*, 197-213. The region where Copernicus spent most of his life, in modern Poland, once included a large German-speaking population. In common with most modern acounts of his life, I adopt German rather than Polish place-names, which does not, however, signify an endorsement of German nationality for Copernicus himself. For a short list of German names important to the biography of Copernicus and their Polish equivalents, see Colin A. Russell, "Copernicus and His Revolution," in *Rise of Scientific Europe 1500-1800*, ed. David Goodman and Colin A. Russell (Sevenoakes, Kent: Hodder & Stoughton and Open University, 1991), 61.

[6] "Item sexternus Theorice asserentis Terram moveri, Solem vero quiescere," Matthew of Miechow, quoted in Swerdlow and Neugebauer, *Mathematical Astronomy*, 8.

details would be a straightforward task and concluded with an optimistic assessment of his success: "And so altogether, Mercury moves on seven circles, Venus on five, the earth on three and the moon moves about it on four, and finally Mars, Jupiter, and Saturn on five each. Therefore, taken as a whole, 34 circles are sufficient to represent the entire structure of the heavens and the entire choric dance of the planets."[7] The final form of his system that appeared in *De revolutionibus* required considerably more circles than he introduced in the *Commentariolus*, since he underestimated the difficulties of reproducing available observations with geometrical models.

Nevertheless, Copernicus' heliocentric cosmology had already reached its final form in the *Commentariolus*. The planets circle the central Sun in the modern order Mercury-Venus-Earth-Mars-Jupiter-Saturn and the fixed stars are truly fixed and motionless, since the motions of the eighth sphere have been transferred entirely to the terrestrial globe. Nowhere did Copernicus reveal the thought process leading him to investigate an astronomy based on the Earth's motion; even though he understood, and explained, many of the advantages it provided over geocentrism (and suppressed some of the disadvantages), he never singled out one as being somehow primary in his thought. Various reconstructions of the prehistory of the *Commentariolus* have been made; the two most plausible are those of Noel Swerdlow and Bernard R. Goldstein. Swerdlow has argued that at an early stage Copernicus contemplated a geoheliocentric system: the Earth would remain at rest at the center of the world with the Moon, Sun, and fixed stars circling around it, while the five planets circled the moving Sun instead. Like Tycho

[7] Copernicus, transl. in Swerdlow, "The Derivation and First Draft of Copernicus's Planetary Theory: A Translation of the *Commentariolus* with Commentary," *Proceedings of the American Philosophical Society* 117 (1973): 510.

Brahe (1546-1601), who published such an arrangement much later in the sixteenth century, Copernicus discovered that the orb of Mars would have to penetrate the orb of the Sun (figure 15). In the Tychonic system the circle of Mars, the innermost of the superior planets, just overlaps the circle of the Sun. The two bodies would never collide because the circle of Mars would move in order to remain centered on the Sun, but Aristotelian physics required that celestial orbs remain inviolate: orbs could not overlap. Unlike Tycho, Copernicus opted to sacrifice terrestrial immobility and centrality in order to retain non-overlapping orbs as the proximate cause for celestial motion.[8]

More recently, Goldstein has argued that Copernicus arrived at heliocentrism as a result of his efforts to resolve the longstanding question of whether a relationship could be found between a planet's speed and its distance from the center of the world.[9] This problem was part of the more general issue of the ordering of the celestial bodies that had confronted astronomy and physics since classical times.

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[8] Swerdlow, "*Commentariolus*," 471-78.

[9] Goldstein, "Copernicus and the Origin of His Heliocentric System," *JHA* 33 (2002): 219-35.

Ordering the Planets from Geminus to Copernicus

In chapter two we considered the explanation given by the ancient scholar Geminus of Rhodes of the work of the astronomer and the physicist. In a passage preserved by Simplicius, Geminus stated that the astronomer investigated "the shapes, sizes, and distances of the Earth, Sun, and Moon."[10] The arrangement and distances of the celestial bodies and the Earth had a long history in Greek studies of nature. Several prominent Greek mathematicians attempted to determine not only the arrangement but also the distances of the celestial bodies and the Earth. The earliest such effort known is the highly speculative cosmic arrangement of the presocratic philosopher Anaximander (ca. 610-546/545 B.C.E.). In the third century B.C.E., Aristarchus of Samos wrote a treatise *On the Sizes and Distances of the Sun and the Moon* describing his procedure for making four key cosmic measurements.[11] Although he did not calculate their absolute values, the procedure leads to values expressed in terms of Earth radii (e.r.) and Earth diameters. His value for the distance of the Sun (380 e.r.) fell considerably short of the modern distance.[12] His method depended on precision in difficult observations, so that even a small difference would lead to a very large error in the distance, and hence the size, of the Sun. In addition, he exaggerated the Moon's apparent diameter, perhaps deliberately. His estimate of 2° is about four times too large. Aristarchus' probably intended to demonstrate that celestial distances could be measured and that the cosmos

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[10] Geminus, translated in Evans, *History and Practice*, 219.

[11] Text and translation in Heath, *Aristarchus*, 351-411.

[12] Completing Aristarchus' calculations actually results in a range of possible values. I have taken approximate values from Albert Van Helden, *Measuring the Universe: Cosmic Dimensions from Aristarchus to Halley* (Chicago: University of Chicago Press, 1985), 8.

was very large, not to find exact values.[13]

Both Hipparchus and Ptolemy sought to improve Aristarchus' values for the sizes and distances of the Sun and Moon by modifying his methods.[14] They also calculated the volume of the Sun and Moon in comparison to the Earth. Ptolemy described his procedure for determining sizes and distances in the *Almagest* as part of his lunar theory. Among celestial objects, only the Moon is so close to the Earth that its parallax influences observations of its apparent position; finding the lunar distance, therefore, is a necessary antecedent to creating an accurate model (figure 16). Ptolemy calculated that the Moon moved between a minimum of 33;33 e.r. and a maximum of 64;10 e.r., and found the mean distance of the Sun to be 1,210 e.r. (appendix 2). The *Almagest* values for Sun and Moon became standard in mathematical astronomy.[15] As the lunar distances show, his lunar theory predicts a noticeable variation in the apparent diameter of the Moon. It should appear to double in size over the course of a month, but in reality, its size appears to remain nearly constant. Both Regiomontanus and Copernicus commented on this flaw in Ptolemaic lunar theory.[16]

Ancient Greek measurements use the Earth as a measuring-stick because their methods involved observation of the Earth's shadow during a lunar eclipse. In the fourth

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[13] For a discussion of the method used by Aristarchus see Evans, *History and Practice*, 68-72; *HAMA*, 2:634-43; and Van Helden, *Measuring the Universe*, 6-9.

[14] Little is known about the life of Hipparchus, who is considered to be one of the most significant Greek astronomers. His work is familiar to us primarily through references in the *Almagest*. Ptolemy credits him with the solar model of the *Almagest* and with the discovery of precession; *HAMA*, 1:274-343.

[15] *Almagest*, 5.11-16, pp. 243-257 explains the difficulty of lunar parallax and calculates sizes and distances relevant to lunar and solar models. Toomer (the translator) suggests volumes were also a traditional element of astronomy in 257 n. 66. For the procedures used by Hipparchus and Ptolemy see Van Helden, *Measuring the Universe*, 10-19; *HAMA*, 1:100-112; and Janice Adrienne Hendersen, *On the Distances between Sun, Moon and Earth According to Ptolemy, Copernicus, and Reinhold*. Leiden: E. J. Brill, 1991.

[16] Regiomontanus, *Epytoma*, 5.21, fol. F4r-v; *De rev*. (1543), 4.2, fol. 100r.

century B.C.E., Aristotle reported the size of the Earth's circumference to be 400,000 stades according to unnamed mathematicians, but he did not describe their method.[17] Eratosthenes (ca. 276-ca. 195 B.C.E.) measured the circumference of the Earth using gnomonic observations and found it to be either 250,000 or 252,000 stades. Posidonius (ca. 135-ca. 51 B.C.E.) measured the Earth's circumference as 180,000 stades. The latter became the more widely accepted value, but both were regarded as authoritative. For example, Sacrobosco refers to Eratosthenes, not Posidonius, in his *Sphaera*.[18]

Distances for the other celestial bodies proved to be more troublesome; even their order could not be determined with certainty.[19] The sole exception was the discovery that the Moon must be closer than the Sun because it covers the latter during a solar eclipse. Since a definitive ordering for the planets could proceed no further mathematically, proponents of any given arrangement resorted to physical justifications. General consensus held that one criterion should be the time it takes a planet to return to the same longitude with respect to the fixed stars. Aristotle argued that the daily westward rotation of the sphere of stars slowed the eastward second motion of each planet, more so in the case of planets nearest the outer sphere.[20]

For some celestial bodies, establishing an order on Aristotle's principle was straightforward. The Moon has the shortest period at one month, while Saturn, Jupiter, and Mars have periods of about 30 years, 12 years, and 2 years respectively. But

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[17] Aristotle, *On the Heavens* 2.14.

[18] For ancient measurements of the Earth see Evans, *History and Practice*, 63-66; and *HAMA*, 2:651-54. On Posidonius' influence see Stahl, 43-61.

[19] My discussion of the problem of the ordering of the planets follows Evans, *History and Practice*, 347-349; and Goldstein, "Copernicus and the Origins of His Heliocentric System."

[20] Aristotle, *On the Heavens* 2.10.

Mercury, the Sun, and Venus all have periods of one year, making their relative ordering problematic. Plato gave the order, from the fixed stars inward, as Saturn, Jupiter, Mars, Mercury, Venus, Sun, Moon.[21] Plato's solution puts the bodies appearing to be largest and brightest near the Earth and groups the five smaller planets together. An alternate arrangement, which served as a cornerstone of Ptolemaic astronomy, placed the planets in the order Saturn, Jupiter, Mars, Sun, Venus, Mercury, Moon (figure 15). In this illustration, the top right figure shows the spheres in the Platonic order; the top left figure, the order that came to be associated with Ptolemy. Advocates of the second arrangement emphasized the centrality of the Sun as the bestower of light and life to the world, the spirit of the world, and the ruler of the celestial realm.[22] A few texts before Ptolemy allude to measurements of the distances of planets other than the Sun and Moon, as Cicero did in *On Divination*, and authors after Ptolemy also referred to non-Ptolemaic measurements. However, they tell us neither how the measurements were made nor, in many cases, how far the planets are from the Earth. A few exceptions exist; for example, a popular handbook author, Ambrosius Theodosius Macrobius (fl. early 5th century C.E.), explains a system in which the ratios of planetary periods are used to determine their relative distance. Saturn, having a period thirty times that of the Sun, is thirty times as distant, while the Moon, having a period one-twelfth that of the Sun, is twelve times

[21] Plato, *Timaeus* 7.38.

[22] Examples include Pliny, *Natural History* 2.4; and Cicero, "The Dream of Scipio," originally a part of his *Republic* but known to medieval readers through the commentary of Macrobius; for translation see Macrobius, *Commentary on the Dream of Scipio*, transl. William Harris Stahl (New York: Columbia University Press, 1952), 73. Even the computist Bede, who was suspicious of astrology and astral religion, compared the Sun to the world's spirit when he made it the central planet; see Bede, *Reckoning of Time*, 33. The image of the Sun as celestial ruler continued into the early modern period, as shown by Keith Hutchison, "Towards a Political Iconology of the Copernican Revolution," in *Astrology, Science, and Society: Historical Essays*, ed. Patrick Curry (Woodbridge, Suffolk: Boydell Press, 1987), 95-141.

closer.[23]

Ptolemy ensured the canonicity of the second order when he included it in the *Almagest*. By placing the Sun as the middle planet, he divided the superior planets, "which reach all possible distances from the sun," from the inferior planets, which have bounded elongation and always appear close to the Sun.[24] In the *Planetary Hypotheses* he argued further that planets with motions unlike the Sun, such as Mercury and the Moon, must be placed at a distance from the Sun, and that planets with more complicated motions must be nearer the elementary realm because they resembled the turbulent air. He introduced what has come to be known as the "nesting hypothesis." Ptolemy assumed that the systems of orbs, or sections of orbs, for the planets were contiguous. Each sphere fit exactly in the next, so the greatest distance of one planet--and the outer surface of its orb--was the same as the least distance of the next planet--and the inner surface of its orb (figures 1 and 17). He already knew the greatest and least distances for the Moon and the Sun, the ratio of least to greatest distances for each of the remaining five planets, and the order of the planets.[25]

Ptolemy calculated the minimum and maximum distances for each planet and the distance to the sphere of fixed stars, which was concentric with the Earth, with remarkable sucess (appendix 2). The results left only a small gap between Venus and the Sun, which could be eliminated by changing the parameters of the *Almagest* models

[23] Cicero, *De Divinatione* 2.43 (see chapter 2); Macrobius, *Commentary*, 166, 176. Stahl, *Roman Science*, 163, identifies Porphyry's third-century commentary on Plato's *Timaeus* as Macrobius' source.

[24] *Almagest*, 9.1, pp. 419-20.

[25] The portion of the *Planetary Hypotheses* on cosmic sizes and distances is translated in Goldstein, "The Arabic Version of Ptolemy's Planetary Hypotheses," *Transactions of the American Philosophical Society*, n.s. 57, part 4 (1967); see especially pp. 5-9.

slightly (though he elected not to take this step). The result was a universe in which the beginning of the celestial realm, the closest approach of the Moon, was 33 e.r. from the center of the world, while the sphere of fixed stars began beyond the outer surface of the sphere of Saturn at about 20,000 e.r. Two Islamic astronomers of the ninth century, al-Farghānī and al-Battānī, used the nesting sphere principle to calculate their own sets of distances that became popular among both Islamic and Latin astronomers. Despite minor disagreement about the distances to some planets, al-Farghānī and al-Battānī came to nearly identical conclusions about the overall size of the universe determined by the minimum distance to the fixed stars (20,110 e.r. and 19,000 e.r. respectively), remaining consistent with Ptolemaic cosmology.[26]

Ptolemy's success in fitting the spheres of Mercury and Venus between the spheres of the Moon and the Sun supported his choice for ordering the planets, but he could offer no way to guarantee its certainty. Any arrangement of the outer planets would be mathematically arbitrary because each epicycle was scaled to fit its deferent. Copernicus noted the uncertainty as part of his critique of geocentrism in *De revolutionibus*:

> Accordingly it will be appropriate either that the Earth is not the center to which the order of the stars and orbs is referred, or else that there is no established rule of order, nor is it manifest why the highest place should be alloted to Saturn rather than to Jupiter or another of them.[27]

Recently Goldstein has argued that Copernicus' investigation of heliocentrism stemmed from his attempt to find verification for the principle that a ratio existed between a

[26] Van Helden, *Measuring the Universe*, 29-40.

[27] "Oportebit igitur, uel terram non esse centrum, ad quod ordo syderum orbiumque referatur: aut certe rationem ordinis non esse, nec apparere cur magis Saturno quàm Ioui se alij cuiuis superior debeatur locus." *De rev*. (1543), 1.10, fol. 8v (my translation).

planet's distance from the center of motion and its period. Martianus Capella (fl. ca. 365-440 C.E.) and Macrobius, among others, had written about a third system that solved the problem of determining the order of Mercury and Venus by placing both planets on epicycles centered on the Sun (figure 15).[28] The system of Martianus Capella is called the "Egyptian System" in this illustration. Copernicus extended the approach to all the planets, thereby providing not only a fixed order and distance for the planets, but also a relationship between their distances and speeds. In Goldstein's view, the manuscripts Swerdlow studied were produced by Copernicus only after he had settled upon heliocentrism as the solution to the distance-period problem.[29]

Whatever reason Copernicus had for departing from accepted cosmology, he did so at a relatively early stage in his life, and we get only glimpses of his work on astronomy between the writing of the *Commentariolus* sometime around 1510, and the first printed description of his work by Rheticus in 1540.[30] Swerdlow and Neugebauer suggest that he found the task of demonstrating the reality of the Earth's motion, against a tradition of terrestrial immobility dating back nearly two millennia, to be nearly impossible. Rather than announce his work and risk public ridicule, he sought irrefutable confirmation that he could never find, since any astronomical model he proposed could be transferred to a geocentric system. The paper used in the manuscript of *De*

[28] For analysis of proposed partial heliocentrists in Antiquity, see Bruce Stansfield Eastwood, "Kepler as Historian of Science: Precursors of Copernican Heliocentrism According to 'De Revolutionibus,' I, 10," *Proceedings of the American Philosophical Society* 126 (1982): 367-94, which is a broader study than its title might imply. For translations of the figures named here, see Martianus Capella, in *Martianus Capella and the Seven Liberal Arts*, vol. 2, *The Marriage of Philology and Mercury*, transl. William Harris Stahl and Richard Johnson with E. L. Burge (New York: Columbia University Press, 1977), 8.879-82, pp. 341-43; Macrobius, *Commentary*, 163-64. Macrobius ascribes the order to the Egyptians.

[29] Goldstein, "Copernicus and the Origins of His Heliocentric System," 221-22.

[30] Georg Joachim Rheticus, *Ad clarissimum virum D. Ioannem Schonerum, de libris revolutionum ... NARRATIO PRIMA* (Danzig: Franciscus Rhodus, 1540). (Subsequently referred to as *NP* (1540).)

revolutionibus indicates that Copernicus did not begin writing it until the 1530s and that it was still incomplete when Rheticus visited him in 1539. During the 1510s and 1520s, he spent his spare time making observations to refine his models.[31] Copernicus did not remain entirely silent on his work during this period. Barker and Goldstein have identified surviving references to Copernicus demonstrating at least limited outside awareness of his heliocentric system before 1538. Besides the reference to the *Commentariolus* in a Cracow library, there are scattered indications that Copernicus had made available at least the bare outlines of his cosmology to a select few.[32] But there is no reason to assume widespread scholarly knowledge that Copernicus had devised an astronomical system founded on the motion of the Earth. The silence of the historical record supports his claim in *De revolutionibus* to have maintained a Pythagorean-like secrecy during his labors.[33]

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[31] On the question of dating composition, see Swerdlow and Neugebauer, *Mathematical Astronomy*, 87-89.

[32] Barker and Goldstein, "Patronage and the Production of *De Revolutionibus*," *JHA* 34 (2003): 347-50. Compare Swerdlow and Neugebauer, *Mathematical Astronomy*, 24, where it is assumed that Copernicus' work on heliocentrism must have been widely known in Germany. All surviving copies of the *Commentariolus* postdate the publication of *De revolutionibus*; Jerzy Dobrzycki and Lech Szczucki, "On the Transmission of Copernicus's *Commentariolus* in the Sixteenth Century," *JHA* 20 (1989): 25-28.

[33] In the letter to the pope prefacing *De rev*. (1543), fol. ijv-iijr.

Terrestrial Motion in *De revolutionibus*

At the time Copernicus wrote the *Commentariolus* he believed that a heliocentric system would be simpler than the Ptolemaic models embedded in the *Alphonsine Tables*, one of the authoritative astronomical texts of his day. The intervening years dashed his hopes. The theory of terrestrial motion found in *De revolutionibus*, incorporating the solar theory and the motions of the eighth sphere from late medieval Ptolemaic astronomy, calls for not three circles, his original estimate, but eight or nine (according to my count), depending on whether the first inequality is considered to be separate from the third motion. Moreover, some create compound variations in the Earth's motion. In the remainder of this chapter, I shall describe the astronomy of *De revolutionibus*, with special attention given to the motion of the Earth, and defer to the next chapter my discussion of the circumstances surrounding its publication.

The theory of the Earth in Copernican astronomy comprises several kinds of terrestrial motion. Book I of *De revolutionibus*, which gives a non-mathematical account of the arrangement of the heavens, describes the "triple motion of the Earth," the simplest and now most famous set of motions.[34] Demonstrations of the factors introducing inequalities into the Earth's motion are reserved for Book III, corresponding to Ptolemy's solar theory in Book III of the *Almagest*.[35] The following outline shows the relationships

[34] As in the chapter title "De triplici motu telluris demonstratio," *De rev*. (1543), 1.11, fol. 10r.

[35] Rheticus' *Narratio prima*, first published in 1540, still remains the best detailed summary of Copernican astronomy. Maestlin added explanations and diagrams of key concepts to the fifth and sixth editions of the *Narratio prima*; Johannes Kepler, *Prodromus dissertationum cosmographicarum, continens Mysterium cosmographicum ... Addita est erudita Narratio M. Georgii Ioachimi Rhetici, de Libris Revolutionum...* (Tübingen: Georgius Gruppenbachius, 1596), 85-160; for an assessment of the additions see Tredwell, "Michael Maestlin and the Fate of the *Narratio prima*," *JHA* 35 (2004): 305-325. For technical but informative descriptions of the motion of the Earth, with attempts to find the derivation of key parameters, see Swerdlow and Neugebauer, *Mathematical Astronomy*, 127-82 and 581-90; Swerdlow, "On Copernicus' Theory of Precession," in *The Copernican Achievement*, ed. Robert S. Westman (Berkeley: University of California Press, 1975), 49-98; and Kristian Peder Moesgaard, "The 1717 Egyptian Years and the

between the various motions assigned to the Earth in *De revolutionibus*.

I)	Triple Motion of the Earth	
	A) First motion (daily rotation)	24 hours
	B) Second motion (annual revolution)	365 days 6;9,40 hours
	C) Third motion (motion of inclination)	ca. 365 days 5;49,36 hours
II)	Librations (Trepidation)	
	A) Anomaly of inclination (variation in obliquity)	3,434 Egyptian years
	B) Anomaly of equinoxes (variation in precession)	1,717 Egyptian years
III)	Inequalities of the Tropical Year (Solar Theory)	
	A) First inequality (eccentric and its motion around center)	ca. 53,000 years
	B) Second inequality (twofold inequality)	3,434 Egyptian years
	1) Variation of eccentricity	
	2) Motion of line of apsides	

The "triple motion of the Earth" includes the most prominent motions. The *first motion* is the daily motion, which is identical to the first motion in Ptolemaic astronomy, save that Copernicus attributes it to the 24-hour rotation of the Earth from west to east rather than a rotation of the entire universe from east to west. The *second motion* is the annual motion of the Earth around the Sun (*motus centri annuus*, "the yearly motion of the center," i.e., the center of the Earth, fol. 10v), causing the Sun to appear to move from west to east along the ecliptic. The solar year can be reckoned in two ways. The sidereal

Copernican Theory of Precession," *Centaurus* 13 (1968): 120-38.

year is defined as the return of the Sun to a fixed star. It is slightly longer than the tropical year, which is defined as the return of the Sun to an equinoctial or solstitial point; Hipparchus and Ptolemy preferred the equinox as a measuring point because it can be measured with greater precision using naked-eye observation and simple instruments. Ptolemy chose the tropical year as his standard because he considered the equinoxes and solstices to be fixed, whereas the fixed stars moved because of precession.[36] Copernicus is vague about the nature of the year in the chapter on the Earth's triple motion, but in the *Commentariolus*, he had already expressed his preference for the sidereal year: "Since the equinoxes and the other cardinal points of the universe move considerably, whoever attempts to derive the uniform annual revolution from them is necessarily mistaken, for it has been found to be irregular by many observations in different ages."[37] The motion of the equinoxes was already known through the theories of precession and trepidation. In *De revolutionibus* he shows that observers since Ptolemy have determined different lengths for the tropical year and concludes that it is variable. He rejects Ptolemy's choice in favor of the nearly invariable sidereal year, which he determines to be 365 d 6;9,40 h in length.[38]

The *third motion* is the annual motion of inclination (*declinationis motus annua*, fol. 10v), which maintains the orientation of the Earth's axis with respect to the fixed stars. As the Earth moves around the Sun, the northern hemisphere is inclined alternately towards and away from the Sun, causing seasonal variations in the lengths of day and night, while its axis always points towards the north celestial pole in the approximate

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[36] *Almagest*, 3.1, pp. 132-33.

[37] Copernicus, translated in Swerdlow, "*Commentariolus*," 451.

direction of the constellation Ursa minor. Were the Earth to be endowed with only two motions, according to Copernicus, its axis would always be inclined the same angle with respect to the Sun, not the stars. The length of the day would be fixed, we would know only one season, and there would be no polestar. The Earth's third motion is a rotation opposite in direction to the annual motion and nearly equal in length (figure 18).[39] In this side view, AEC is the plane of the ecliptic; the Earth revolves around the Sun E once a year. DF is the axis of the Earth's daily rotation. The third motion is a rotation on an imagined axis perpendicular to the ecliptic in a direction opposite to the yearly motion. The length of daylight changes as the north pole D inclines first towards, then away from the Sun.

However, Copernicus must also account for precession. Over very long periods of time the Earth's axis does not maintain its orientation with respect to the fixed stars, with the result that the equinox--the point where the ecliptic and equator appear to cross--slowly moves through the zodiac. By assigning to the third motion a period slightly shorter than the period of the second motion, Copernicus creates precession of the equinoxes. According to Rheticus, the period of the motion of inclination is about 365 d 5;49,36 h, making it 0;20,4 h shorter than the sidereal year.[40] When the motion of inclination is complete, the Earth will have completed only 359;44,49,7,4° of its yearly circle around the Sun. Looked at another way, the Earth's axis will have completed its

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[38] *De rev*. (1543), 3.13-14, fols. 78v-81r.

[39] In modern terms, the third motion is unnecessary; the Earth's axis naturally maintains its inclination as it moves through space. Possibly Copernicus felt the need to include the third motion because he thought of the Earth as a body enclosed in an aetherial orb. Similarly, a nail hammered into the rim of a wheel always points towards its center of motion. However, he is not explicit concerning why this motion is necessary.

[40] *NP* (1540), fol. B4r, where it is given as 365;14,34 d. I have taken the conversion to conventional time units from Rosen, *Three Copernican Treatises*, 128 n. 85.

motion of inclination in one sidereal year and gone slightly further. The third motion and precession are distinct concepts; the first causes the second. The motion of inclination is nearly equal to the annual motion, while the mean motion of precession created by the interaction of the two motions completes a revolution in 25,816 Egyptian years.[41]

Terrestrial motion in *De revolutionibus* includes several additional motions that may be divided into two groups: motions that introduce variations into the orientation of the Earth's axis with respect to the stars, and motions that introduce variations into the yearly motion of the Earth's center around the Sun (or mean Sun). Copernicus gives the name librations (*librationes*) to the two motions of the Earth's axis, which must be distinguished from the motion of inclination. They create apparent variations in terrestrial motion called the *anomaly of inclination* or the *single anomaly*, and the *anomaly of the equinoxes* or the *double anomaly*.[42] The librations create the changing obliquity of the ecliptic and the unequal motion of the equinoxes. The *Alphonsine Tables* and the *Theoricae novae planetarum* treated these phenomena as the result of the trepidation of the eighth sphere. Trepidation theory is one of several places in *De revolutionibus* where Copernicus introduces astronomical devices also used by Islamic astronomers during the thirteenth and fourteenth centuries.[43]

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[41] "We said moreover that the annual revolutions of the center [i.e., the second motion] and the declination are nearly equal," "Dicebamus autem centri & declinationis annuas reuolutiones propemodum esse aequales. . . ." *De rev*. (1543), 1.11, fol. 11v (my translation). Copernicus gives the distance the Earth travels in one motion of inclination in 3.14, fol. 81r and the value for the mean motion of precession in 3.6, fol. 69v.

[42] E.g., "primam ac simplicam illam anomaliam obliquitatis," *De rev*. (1543), 3.21, fol. 92r; "anomalia duplex," 3.11, fol. 77r; see also Copernicus, *The Manuscript of Nicolas Copernicus' 'On the Revolutions' Fascimile*, Nicolas Copernicus Complete Works (London and Warsaw: Macmillam and Polish Science Publications, 1972), fol. 82r, where Copernicus states that the double anomaly is the anomaly of the equinoxes. The manuscript passage is translated in *On the Revolutions*, transl. Edward Rosen (Baltimore: Johns Hopkins Press, 1978), 135.

[43] For a list of parallels between Copernicus and Islamic astronomers see E. S. Kennedy, "Late Medieval

The Latin noun *libratio* comes from the verb *libro*, *librare*, "to swing." Copernicus proposes that the poles of the Earth oscillate. Like objects suspended in the air, the motion of the poles is swifter near the middle of the libration and slower near its limits. The poles oscillate simultaneously in two directions at right angles; furthermore, the periods of the librations are commensurable and the two motions reach their center at the same time. The period of one is twice that of the other. Their combined motion causes each pole to trace out a small figure eight (figure 19). In Copernicus' diagram the motions in libration begin with the north pole at F. The pole oscillates between F and G with a period of 3,434 Egyptian years. In this interval, it will swing through the central point I to G and back to F. At the same time, it oscillates perpendicularly with a period of 1,717 Egyptian years. In this time, the pole will swing from F through K, I, and L before ending a cycle at G. The 1,717 year cycle repeats, while the 3,434 year cycle completes itself, and the pole moves from G through M, I, and N, completing the set of librations at F.[44]

The librations of the poles have their counterpart in motions of the Earth's equator. The 3,434 year cycle is the motion of the anomaly of the inclination. The obliquity of the ecliptic, the angle at which the ecliptic meets the equator, was known to

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Planetary Theory," *Isis* 57 (1966): 377. A possible route of transmission via Byzantine translations of Arabic and Persian astronomical texts, subsequently brought to Italy, has been suggested by Neugebauer, "Studies in Byzantine Astronomical Terminology," *Transactions of the American Philosophical Society*, n.s., 50, part 2 (1960): 1-45, although Greek or Latin translations of the texts thought to have influenced Copernicus have not been found. More recently, a connection through Vienna and the work of Peurbach and Regiomontanus has been argued by Jerzy Dobrzycki and Richard L. Kremer, "Peurbach and Marāgha Astronomy? The Ephemerides of Johannes Angelus and Their Implications," *JHA* 27 (1996): 187-237. For a recent assessment of the literature on the Islamic influence on Copernicus, see F. Jamil Ragep, "Copernicus and His Islamic Predecessors: Some Historical Remarks," *Filozofski vestnik* 25 (2004): 125-42.

[44] Copernicus explains the librations of the poles in *De rev*. (1543), 3.3, fol. 65v-67r, and gives their periods in 3.6, fol. 69r-70r.

have decreased since Ptolemy's time. Copernicus, following existing trepidation theory, believed that it alternately decreased and increased, but he assigned it a different sort of motion. The poles oscillate along a great circle over an arc of 0;24° (0;12° to either side of the mean poles) passing through the solstitial points, where the ecliptic reaches its greatest separation from the equator. The libration moves the equator towards, then away from, the ecliptic. (Note that for Copernicus the ecliptic, as determined by the Earth's annual motion is fixed, while the equator shifts with the axis of rotation. The Alfonsine theory of the eighth sphere assumed a fixed celestial equator and a moveable ecliptic on the eighth sphere.) The obliquity of the ecliptic varies between the extremes of 23;52° and 23;28°--a range of 0;24°. According to Copernicus it had nearly reached its minimum and would begin to increase shortly.[45]

The 1,717 year cycle is the motion of the anomaly of the equinoxes. The poles oscillate along a great circle passing through the mean equinoxes, over an arc of 0;56° (or 0;28 to either side of the mean poles). When the true pole coincides with the mean pole at the midpoint of the librations (the cross at the center of the figure eight), the mean equinoxes coincide with the true equinoxes. As the poles oscillate, however, the corresponding points on the equator shift above and below the ecliptic. The true equinoxes, where the equator crosses the ecliptic, oscillate or "trepidate" about the mean equinoxes (figure 12). In this diagram, A is the first star of Aries (γ Arietis) on line AB, the ecliptic. The third motion (motion in inclination) causes a conceptual mean equator to

[45] The extremes Copernicus assigns to the anomaly of inclination lie just outside the observed maximum (23;51,20° as determined by Ptolemy) and minimum (about 23;28,30° according to his own observations). According to Copernicus, Aristarchus found the obliquity to be the same value as did Ptolemy, a sign that the libration was at its extreme where it moves most slowly. Copernicus explains the method of determining the obliquity in *De rev*. (1543), 2.2, fol. 28v-29r, and gives the relevant history of observations in 3.2, fol. 64r-65r, and the limits of its motion in 3.10, fol. 76r-v.

move at a constant speed; the mean equinox is at C, where it crosses the ecliptic. C precesses uniformly away from the star and will complete a circuit of the ecliptic in 25,816 years. Additionally, the librations shift the equator within the circle of anomaly DE, causing the true equinox (where the visible equator crosses the ecliptic) to oscillate around the mean equinox along the diameter of the circle. The diagram records several historical observations. In the time of Hipparchus (2nd century B.C.E.), the equinox was at F; in Ptolemy's day (2nd century C.E.) it was at G; and at the time of al- Battānī (9th century) it was at H. The anomaly of the obliquity enhances trepidation, for which reason Copernicus calls the anomaly of the equinoxes the "double anomaly." The combined effect of both librations is to shift the true equinox over an arc of 2;20° on the ecliptic, which is 1;10° (70') on either side of the mean equinox.[46]

Physical doctrine prevented Copernicus from simply postulating oscillations of the poles without a causal mechanism. "However, someone will indeed ask how the equality of those librations could be understood, when in the beginning it is said that celestial motion is equal, or composed from equal and circular [motions]."[47] Copernicus knew how to generate straight-line motion from a combination of circular motions using a mathematical device that has come to be known as a Tūsī couple (figure 20). Today, the two-dimensional version of the device is normally conceived of as two circles, one with half the diameter of the other and placed inside the larger circle so that their circumferences touch. As the large circle rotates in one direction, the other rotates in the

[46] Copernicus gives the limits for the second libration in *De rev*. (1543), 3.7, fol. 73r.

[47] "Interim uero quaeret aliquis, quo nam modo possit illarum librationum aequalitas intelligi, cum à principio dictum sit, motum celestem aequalem esse, uel ex aequalibus ac circularibus compositum." *De rev*. (1543), 3.4, fol. 67r (my translation). The principle first appears in the book in 1.4, fol. 2v-3r.

other in half the time. In Copernicus' diagram, the cycle would begin with point H on the circumference touching the larger circle at the top. As the two circles rotate, H oscillates along diameter AB. Copernicus uses a slightly different construction of the Tūsī couple in *De revolutionibus*, based on two circles of identical size. In this version, the central circle carries the center F of the second circle as it rotates. As the central circle rotates, the second circle rotates in the opposite direction at twice the speed, causing H to oscillate along AB, moving more swiftly near the center and more slowly near the limits.[48]

Copernicus alluded casually to knowledge of the Tūsī couple in a passage in the manuscript of *De revolutionibus*, struck from the printed version, commenting that "some people call this motion on the breadth of a circle."[49] The device was used for very different purposes by two contemporaries of Copernicus in Italy, Giovanni Battista Amico and Girolamo Fracastoro. All three men may have obtained their knowledge from an unidentified common source in Italy where Copernicus studied astronomy. Knowledge of the Tūsī couple may have reached Italy through a chain of transmission reaching back to Nasir al-Dīn al-Tūsī, director of the Islamic Marāgha observatory in the thirteenth century.[50]

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[48] Copernicus explains the couple in *De rev*. (1543), 3.4-5, fol. 67r-68v. For technical discussions of the Tūsī couple see Ragep, "The Two Versions of the Tūsī Couple," in *From Deferent to Equant: A Volume of Studies in the History of Science in the Ancient and Medieval Near East in Honor of E. S. Kennedy*, ed. David A. King and George Saliba (New York: New York Academy of Sciences, 1987), 329-56, who demonstrates the difference between the plane version and a spherical version not used by Copernicus; and Mario di Bono, "Copernicus, Amico, Fracastoro and Tūsī's Device: Observations on the Use and Transmission of a Model," *JHA* 26 (1995): 133-54, who argues, perhaps too strongly, that the construction in *De revolutionibus* should be treated as a third, separate version.

[49] "Vocant autem aliqui motus hunc in latitudinem circuli," Copernicus, *Manuscript*, 3.4, fol. 75r.

[50] On Amico see Noel Swerdlow, "Aristotelian Planetary Theory in the Renaissance: Giovanni Battista Amico's Homocentric Spheres," *JHA* 3 (1972): 36-48. A comparison of details of Copernicus' models with the work of the Marāgha school, suggesting a connection between the two, can be found in Willy Hartner, "Copernicus, the Man, the Work, and Its History," *Proceedings of the American Philosophical Society* 117 (1973): 413-22.

Copernicus explains his understanding of the effect of the librations on precession with the simple concept of a quartered circle. This circle does not represent a circle or sphere in the heavens; it is a way of understanding the cyclical change of speed created by combinations of circular motion, as the dial of a watch represents the passage of time. When the speed of motion is at the top of the circle (the beginning of the first quadrant), the rate of precession is at its minimum. Ptolemy made his observations just after this time, when the motion had entered the first quadrant and was beginning to increase. When it enters the second quadrant, the rate of precession is increasing and has reached its average speed. It continues to increase as it moves through the lower right quadrant until reaching its maximum at the bottom of the circle. According to Copernicus, the rate of precession had just begun to decrease in his own day, signifying that it had recently entered the third quadrant. When it entered the fourth quadrant it would again be at the average speed and it would continue to decrease until it returned to the top of the circle. The same principle ruled the libration of the obliquity of the ecliptic. In Ptolemy's time, obliquity was at its maximum, but its rate of change was at minimum. In Copernicus' day, both the obliquity itself and its rate of change were at the minimum.[51]

The final set of motions to be discussed are the two inequalities of the tropical year. These inequalities are distinguished from the librations, which also affect the length of the tropical year, by the fact that they result from changes in the motion of the Earth around the Sun (second motion) instead of changes in the orientation of its axis (third motion). The first inequality resembles the solar theory of Ptolemaic astronomy. In the *Almagest*, the Sun is moved on an eccentric circle with a fixed apogee and apsidal line

[51] *De rev*. (1543), 3.6, fol. 69r-70r.

(an imaginary line passing through a planet's apses, or apogee and perigee). Ptolemy considers two solar models: an eccentric, and an epicycle on concentric. As proven by Apollonius of Perga, the epicyclic model creates the same appearances as the eccentric one given the correct parameters: the epicycle rotates with the same period as the deferent but in the opposite direction, and the radius of the epicycle is equal to the eccentricity. Ptolemy selected the eccentric model for the Sun because it was simpler: it required one motion instead of two. Medieval astronomers determined that the solar apogee was not fixed. The solar theory presented in astronomical textbooks at the time of Copernicus included an eccentric with a moving apsidal line, but no mention of an epicyclic model.

Because *De revolutionibus*, like the *Almagest*, derives its models from observations (unlike the textbooks, which present the models as given), it compares the eccentric and epicyclic models. Copernicus first considers the case of an epicycle with a period equal to its deferent (figure 21). In Copernicus' diagram, circle ABC is a concentric deferent centered on D, the center of the universe. B is the center of the epicycle. As the deferent moves counterclockwise, carrying the epicycle, planet F is carried clockwise by the epicycle and traces out an eccentric circle GF with eccenter K. The apsidal line passing through the apogee G will remain fixed.[52] Changing the parameters will cause the apsidal line to move (figure 22). If the epicycle has a shorter period than the deferent, as in the diagram at top of the page, the apogee N and the line of apses NMLD will rotate clockwise. If the epicycle has a longer period, the line of apses will rotate counterclockwise, as in the lower diagram. The epicyclic models are observationally indistinguishable from eccentric models in which the eccenter L moves in

[52] The correct modern term for the point in a planet's orbit furthest from the Sun is "aphelion"; however, Copernicus uses the older term "apogee" in explaining the solar model.

a circle around the center of the world D in either a clockwise or counterclockwise direction. The motion of the eccenter, moving eastward (counterclockwise) around the center of the world, is the same as the mean motion in longitude of the apogee or of the apsidal line. Copernicus does not give the period of the mean motion of the apogee, but since its annual motion is 0;0,24,20,14º it will complete a revolution in about 53,000 years.[53]

The final element in Copernican solar theory is the second variation of the tropical year. For convenience, I shall describe the interaction of this motion with the first inequality solely as an eccentric on an eccentric, although Copernicus demonstrates that the motions can also be modeled as an epicycle on an eccentric deferent, or as an epicycle on an epicycle on a concentric deferent (figure 23). In Copernicus' diagram, D is the globe of the Sun and the center of the universe. Near it is C, the center of the eccentric circle AB, which is a heuristic tool, not a deferent. The Sun lies entirely outside a small circle EF that shares the center C. This is the "small circle" (*circulus parvus*) of Copernican astronomy. The deferent of the Earth is the second large circle; its center moves westward (clockwise) on the small circle. In the diagram, the center of the Earth's deferent is placed at G; the line of apses passes through G and K. The second variation has two observable consequences. First, the eccentricity of the solar model changes from a maximum at E to a minimum at F. Second, the motion of the apogee is not uniform, as its mean motion is alternately enhanced and counteracted by the second inequality.[54] The period of the second variation is equal to the period of the anomaly of obliquity, which is

[53] Copernicus demonstrates that the models are interchangeable in *De rev*. (1543), 3.15, fol. 84v-86v. He gives the annual mean motion in 3.22, fol. 93r.

[54] Copernicus explains the second inequality in *De rev*. (1543), 3.20, fol. 90v-92r.

3,434 Egyptian years. Over this period of time, the eccentricity varies between 417 (where the radius is equal to 10,000, about 2;30,7º), just over Ptolemy's eccentricity of 415--and 321 (about 1;55,34º), just under the eccentricity of 323 measured by Copernicus.[55]

[55] *De rev*. (1543), III.21, fol. 92r-93r. Swerdlow and Neugebauer, *Mathematical Astronomy*, 162-63, conclude that Copernicus selected the extremes of the eccentricity to fit the available observations.

Planetary Astronomy in *De revolutionibus*

The remaining planetary models shall be treated only briefly, with attention given to how they might have been thought to improve on existing models. In Sacrobosco's summary of Ptolemaic planetary models at the end of his *Sphaera*, the motion of each planet (except the Sun) has three components: an eccentric circle, an epicycle, and an equant. Sacrobosco's explanation shows that his lunar "equant" is the device now called an evection or a "crank."[56] Not all medieval Latin texts assign an equant to the Moon; Peurbach, for instance, explains the lunar model without using the term. Sacrobosco is one of a number of Latin astronomers who applied the name equant to a class of devices creating motion that was not uniform: one example was the lunar "equant," another was the equant found in the models for the superior planets and Venus.

Ptolemy himself fails to provide names for these devices. In explaining equant motions, he observes that the equant motion for Mercury is different from that of the other four planets but similar to a device in the lunar model.[57] Each model included a motion considered by astronomers to be nonuniform and therefore physically problematic. Hence, Copernicus could write of the Ptolemaic lunar model that "while they allow that the motion of the center of the epicycle is equal around the center of the Earth, it is also proper that they allow that it is unequal in its own eccentric circle, which it describes."[58] Copernicus replaced the old lunar theory with an epicycle on an epicycle,

[56] For an explanation of Ptolemy's lunar model see Pedersen, *Survey*, 184-92.

[57] *Almagest*, 9.5, p. 443.

[58] "Dum enim fatentur, motum centri epicycli aequalem esse circa centrum terrae, fateri etiam eportet inaequalem esse in orbe proprio, quem describit, eccentro." *De rev*. (1543), 4.2, fol. 99r (my translation).

carried on a concentric deferent.[59] Not only did this eliminate the problematic equant with uniform circular motions, but it also avoided the extreme variations in the Moon's distance predicted by Ptolemy's model. For the three superior planets, Copernicus uses an eccentric deferent carrying a small epicycle, also a replacement for the equant mechanism.

Copernicus recalculated the distances of the planets, measuring from the center of the Earth's motion near the Sun, for all planets except the Moon. As was the case in the Ptolemaic nesting system, the Sun and Moon were the only bodies with distances susceptible of direct measurement; distances of the other planets had to be found in terms of the two luminaries (appendix 3). Copernicus found the minimum and maximum lunar distances to be 52;17 e.r. and 68;20 e.r., a substantial improvement over Ptolemy's distances because they require no great change in the apparent size of the Moon. From the Moon's distance, he calculated the distance of the Sun to be 1179 e.r. at apogee and 1105 e.r. at perigee in his own time. Because the Earth's eccentricity had approached its own minimum, the extremes of the Sun's distance more closely approached each other than they had in ancient times. The mean distance he found to be 1142 e.r.--nearly 19 times the mean distance of the Moon, the same ratio that had been determined by Aristarchus and used by Ptolemy.[60]

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[59] For a summary of the models for the Moon and the five planets in *De revolutionibus*, see J. L. E. Dreyer, *A History of Astronomy from Thales to Kepler* (New York: Dover, 1953), 333-42; and Evans, *History and Practice*, 420-22 (superior planets only).

[60] For Copernicus' discussion of lunar and solar distances in *De rev*. (1543), see 4.15-21. Hendersen, *Distances between Sun, Moon and Earth*, has shown that Copernicus modified his calculations to find an expected value, probably a solar distance approximating that of Ptolemy. See also Van Helden, *Measuring the Universe*, 44-46.

Copernicus enjoyed a great advantage over Ptolemy in the determination of planetary distances. Ptolemy had been able to determine with certainty only the ratio of minimum to maximum distance for each planet, based on its eccentricity and the relative size of its epicycle. Although Copernicus included epicycles in his system, they did not serve the same function as the Ptolemaic epicycles, which create retrogradation. That function was taken over by the Earth's motion around the Sun, so we can say that the "great orb" of the Earth is the Copernican equivalent of the planetary epicycles--and this value was already known. Copernicus calculated the distance of each planet from the center of the world in terms of the Earth's distance. For the first time, planetary distances and ordering were inherent in the mathematical models and did not have to be assumed from physical doctrines. Absolute distances could be found (although Copernicus did not give them in *De revolutionibus*) by entering the value for the Earth's distance into the known relative distances (the procedure I have followed for the values in appendix 3). The sole exception was the sphere of fixed stars, which, being motionless, had no model with components that could be used to fix a ratio. Copernicus could only assume that the sphere of fixed stars was so large that the orb carrying the Earth as well as the globe of the Earth itself diminished into insignificance by comparison.[61]

The Copernican system required three radical revisions of the existing system of celestial distances, none of which were explored in detail by Copernicus in *De revolutionibus*. First, the nested-sphere hypothesis was abandoned in favor of fixed distances with sizeable gaps between the planetary orbs. These gaps might contain aether, or they might be true voids, but they serve no purpose in planetary motion, making them

[61] *De rev*. (1543), 1.6, 1.10.

wasted space (figure 24). The problem becomes most acute where the outer planets are concerned, where it becomes obvious that the spheres of the planets occupy only a small region in comparison to the planetary gaps. Second, except for the Sun and Moon, which retain distances relative to the Earth similar to their distances in the *Almagest*, planetary distances are actually less than they were in Ptolemaic astronomy. The maximum size of the sphere of Saturn, the outermost planet, is 19,865 e.r. according to the *Almagest* but only about 11,073 e.r. based on the models in *De revolutionibus*.[62] Third, the sphere of fixed stars becomes immense, and a vast gap, much larger than any of the planetary gaps, opens between it and the sphere of Saturn (figure 25). In a diagram drawn to scale, it would be impossible to depict the enormous space, which early Copernicans compared to something infinite.

[62] Van Helden, *Measuring the Universe*, 44, 47, discusses the wasted space and the reduced planetary distances of Copernican astronomy.

Conclusions

De revolutionibus provided a wide range of new possibilities for sixteenth-century astronomers. Some of its innovations concerned large-scale system-building, as in the determination of a planet's true place in the universe. Others concerned the details of mathematical models of the planets, as in the determination of a new period for the cycle of trepidation. Only a very few chose to adopt the Copernican system in all its details. Even several among the small number of people who can truly be called "Copernican" in the sense of adopting heliocentrism as a real description of the physical arrangement of the cosmos--only about a dozen are known--differed with Copernicus on important points.[63] On the other hand, one did not have to be a Copernican to take up certain of his innovations. The lunar model, for example, could be introduced into a geocentric system without modification, while the motions of the Earth could be transferred to the Sun or the sphere of fixed stars.

This dissertation is not exclusively about Copernican astronomy, but Copernicus is a recurring theme in the astronomical literature written after 1540, and we shall find his name mentioned on a regular basis. In the next chapter I discuss the efforts of four Lutheran mathematicians to incorporate Copernicus into the astronomical reform initiated by Melanchthon. First conceived as a program to complete the perfection of Ptolemaic astronomy begun by Regiomontanus, the Lutheran reform of astronomy ultimately contributed to the downfall of Ptolemy, though the end of that process goes beyond the limits of this dissertation. In chapters five and six I turn to mathematical writings in England. From the 1550s onward, many writers felt the need to address Copernican

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[63] Tredwell and Barker, "Copernicus' First Friends: Physical Copernicanism from 1543 to 1610," *Filosofski vestnik* 25 (2004): 143-66.

astronomy in works on the heavens, and they often did so by referring to Lutheran intermediaries. The points they chose to criticize, and those they readily adopted, help to illuminate the interests of Tudor authors.

CHAPTER 4

THE LUTHERAN REFORM OF ASTRONOMY

In chapter 2 we saw how Melanchthon promoted the study of astronomy and of arithmetic and geometry as preparation for astronomy. Especially after 1531, he praised astronomy for providing knowledge about God's providential plan of the world. Under his influence, a number of students became proficient in astronomy and mathematics. They, and the students they trained in turn at the University of Wittenberg, spread Melanchthon's astronomical program to key figures at other Lutheran universities in German-speaking areas. Ultimately their influence moved outside the domain of the schools to court culture in the works of Tycho Brahe and Johannes Kepler.

Sixteenth-century writers sometimes spoke of the restoration or reforming of astronomy. In their view, the fifteenth century Viennese astronomers Georg Peurbach and Johannes Regiomontanus had achieved or at least initiated the restoration of astronomy, and the *Epitome* stood next to the *Almagest* itself as the central text of Ptolemaic reform.[1] This book not only explained but in some cases added to the material in the *Almagest*, such as by including observations made subsequent to Ptolemy. Lutheran astronomers, however, felt the reform of astronomy was not yet complete and set about looking for a way to finish what Regiomontanus had begun. In 1539, one of them came across a most unlikely reformer: Nicolaus Copernicus. Chapters 4 and 5 examine the development of

[1] Thorndike, *History of Magic and Experimental Science*, 5:332-35.

the Lutheran reform of astronomy through the works of four key mathematicians. This chapter considers the work of Georg Rheticus, who made a brief appearance in chapter 2. When he traveled to Frauenberg in 1539, he found that Copernicus had a nearly complete manuscript of *De revolutionibus* defining heliocentric astronomy in essentially the form described in the previous chapter. Now I turn to the reaction of Rheticus to his discovery: what he admired in the new astronomy and why. I also discuss famous statements by Luther and Rheticus about the possibility of terrestrial motion.

Chapter 5 covers the work of the mathematicians Erasmus Reinhold, Caspar Peucer, and Michael Maestlin. I made brief mention of Reinhold in chapter 2. Reinhold, Rheticus, and Peucer all studied and taught at the University of Wittenberg and can be counted as part of the "Melanchthon circle." Maestlin, the final Lutheran astronomer in this study, represents the transformation of Lutheran astronomy by a later generation. They allow us to see how a like-minded group of mathematicians taught their art in a university context, as well as holding our interest for their role in bringing Copernican astronomy to the attention of the scholarly world. Moreover, all four were read, cited, and in some cases even translated by Tudor writers. As I show in later chapters, the writings of Lutheran astronomers played a crucial role in providing the English with knowledge of Copernican astronomy.

Georg Joachim Rheticus (1514-1574)

The first of our Lutheran astronomers is Georg Rheticus (born Georg Iserin in Feldkirch, in present-day Austria), who appeared briefly in chapter 2 as a promoter of *computus* at Wittenberg. Forced to give up his original surname after his father's execution for heresy, Georg adopted the name "Rheticus" as a reference to the region of his birth.[2] Melanchthon related that Rheticus came close to abandoning his scholarly work at one point, but was encouraged to continue by the influence of Achilles Pirminius Gasser (1503-1577), who remained a close associate of his for many years.[3] He attended Wittenberg, where he received his degree in 1536, and was appointed to the chair of lower mathematics. As we saw in chapter two, his new position required him to lecture on arithmetic, basic geometry, and Sacrobosco's *sphaera*.

In 1538 Rheticus obtained leave to travel Europe. His first stop was Nuremberg, the city where Regiomontanus had set up his printing press, now an important center for mathematical sciences and instrument-making in northern Europe. There he met Johannes Schöner (1477-1547), who had taught mathematics at the Melanchthon Gymnasium since 1526. Schöner had come into possession of manuscripts formerly belonging to Regiomontanus and was engaged in publishing them in collaboration with a leading scientific printer of Northern Europe, Johannes Petreius (1497-1550), whom Rheticus also met.[4] Rheticus went on to Ingolstadt, Tübingen, and Feldkirch (where he

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[2] Biographical information on Rheticus from Burmeister, *Rhetikus*.

[3] The standard biography of Gasser is Burmeister, *Achilles Pirmin Gasser, 1505-1577: Arzt und Naturforscher, Historiker und Humanist*, 3 vols. (Wiesbaden: Pressler-Verlag, 1970-75). Melanchthon mentions Gasser's influence on Rheticus in the *Computus* preface translated in appendix 1.

[4] For an overview of Petreius' printing activities see Joseph C. Shipman, "Johannes Petreius, Nuremberg Publisher of Scientific Works, 1524-1550. With a Short-Title List of His Imprints," in *Homage to a Bookman: Essays on Manuscripts, Books and Printing Written for Hans P. Kraus on His 60th Birthday Oct.*

visited Gasser), finally reaching Frauenburg, the home of Copernicus, in May of 1539. His intention and original itinerary are unknown to us. Jesse Kraai has argued that he left Wittenberg because of his associations (however tenuous) with a group of young students including the scatological poet Simon Lemnius, who had fled in the middle of the night with aid from Melanchthon.[5] Although Rheticus himself would later be forced to flee Leipzig when accused of sexual impropriety, his later history must be weighed against the absence of any signs of long-term problems at Wittenberg. He returned there to teach astronomy and served as dean of the arts faculty for the winter semester beginning October 18, 1541. At this point the sober explanation that Rheticus wished to meet and establish professional contacts with his colleagues seems more probable. However, we cannot rule out the possibility that the scandal of his associates was a contributing factor in his decision to leave Wittenberg temporarily.

Whether he intended to visit Copernicus from the beginning of his trip is another mystery. Rheticus later wrote, "I heard of the fame of Master Nicolaus Copernicus in the northern lands, and although the University of Wittenberg had made me a Public Professor in those arts, nonetheless, I did not think that I should be content until I had learned something more through the instruction of that man."[6] In their study of the events leading to publication of *De revolutionibus* and Rheticus' own *Narratio prima*, Barker and Goldstein observe that what Rheticus said in no way requires him to have heard of Copernicus while he was still physically present at Wittenberg. They conclude that Rheticus reached the decision to travel on to Frauenberg only after arriving in

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12, 1967, ed. Hellmut Lehmann-Haupt (Berlin: Mann Verlag, 1967), 147-162.

[5] Kraai, "Rheticus' Heliocentric Providence," 65-74.

Nuremberg, and that learning about Copernicus' new cosmology may not have been a major factor in his decision. In their view, it is equally likely that the visit was suggested to Rheticus by individuals interested in obtaining observational data or tables from Copernicus. He brought Copernicus a gift of several books, some of which had been printed by Petreius. They may have been sent by the printer as a sample of his workmanship, which would require that Frauenberg was included in Rheticus' itinerary no later than his departure from Nuremberg. In August of 1540, after Rheticus had brought Copernicus to the attention of the mathematical community, Petreius affixed a letter addressed to Rheticus to a book from his press. In the letter Petreius advertised only an interest in Copernicus' observations.[7]

When Rheticus reached Frauenberg, the manuscript of *De revolutionibus* was essentially complete, though slight discrepancies between the models as reported by Rheticus and their final published form show that Copernicus must have continued to refine his work nearly until the end. Rheticus quickly learned the fundamentals of Copernican astronomy in a fairly short time, then wrote a semi-technical treatise in the form of a letter to Schöner reporting on Copernicus' main innovations. According to his own report, at the time Rheticus wrote Schöner he had mastered the first three books of *De revolutionibus*, which included the technical material on the Earth's motion, had generally understood the lunar model, and was working on the planetary models and motion in latitude. Since he arrived in Frauenberg in the second half of May, and

[6] Rheticus, from a letter to Heinrich Widnauer in 1542, translated in Westman, "Melanchthon Circle," 183.

[7] The letter was added to Antonius de Montulmo's *De iudiciis nativitatum liber praeclarissimus*, a fourteenth-century astrological work. A transcription and German translation of the letter are in Burmeister, *Rheticus*, 3:21-25, and an English translation is in Swerdlow, "Annals of Scientific Publishing: Johannes Petreius's Letter to Rheticus," *Isis* 83 (1992): 270-74.

completed the writing of his letter near the end of September, Rheticus must have thrown himself into his studies under Copernicus with great energy. This public letter is far more compact than *De revolutionibus*, in part because Rheticus omitted the demonstrations of motions and derivations of parameters from observations, but it is in some ways more advanced than a *theorica* because Rheticus gives some of the key observations and parameters. Today it is known simply as the *Narratio prima*, which can be translated as "First Account" or "First Report." The first edition was published in March 1540, and the second, with a new prefatory letter by Gasser, in 1541.[8]

The *Narratio* contains sixteen sections indicated by marginal headings, most devoted to the new cosmology and the motion of the Earth. Sections one through six cover the length of the tropical year and the anomaly of the equinoxes, the anomaly of obliquity, and the changing eccentricity. However, Rheticus initially presents them as motions of the Sun and of the fixed stars, saying nothing about terrestrial motion. Section seven covers the lunar model and the elimination of the equant in the models for the Moon and the five planets. Sections eight through ten introduce and defend heliocentrism and the motion of the Earth. Section eleven explains the triple motion of the Earth, and section twelve the librations. Sections thirteen through fifteen briefly explain the models for the five planets; more detailed expositions of planetary motions were to be included in a second *narratio*, which was never published and apparently never written. A long final section "In Praise of Prussia" bears no obvious connection to Copernican astronomy. It may, however, signify that through the book Rheticus attempted to establish a patronage

[8] Rheticus summarizes his studies in *NP* (1540), fol. A2r-v. For dates see Marian Biskup, *Regesta Copernicana (Calendar of Copernicus' Papers)*, Studia Copernicana 8 (Wrocław: Polish Academy of Sciences Press, 1973), 181 no. 429 (Rheticus writes Schöner from Poznan May 14); 184 no. 428 (Rheticus is finishing *Narratio* September 23).

connection with the Duke of Prussia.[9]

Terrestrial motion in the *Narratio* is essentially identical to the model of *De revolutionibus* as described in the last chapter, and there is no need to repeat it here. Yet historians consider Rheticus to be the first Copernican--that is, the first person known to have adopted Copernicus' cosmology as a true description of the universe--and the *Narratio* is regarded as the first Copernican publication. Indeed, for about three years it was the only Copernican publication, making it the sole public source of information on the new astronomical models. His defense of heliocentrism merits our attention as it includes most of the advantages adduced by early Copernicans. It remained an important Copernican document until the end of the sixteenth century.[10]

Rheticus mentions many advantages of Copernican models throughout the *Narratio*. Some of the advantages are independent of cosmological issues. His strongest arguments for the new cosmology are collected in the eighth section under the heading "Principal reasons why the hypotheses of Ancient Astronomers should be withdrawn," which I have translated in appendix 4.[11] Rheticus lists six advantages. First, terrestrial motion provides the most satisfactory explanation of precession and the decreasing obliquity of the ecliptic. This includes the variation in precession, so that the entire theory of trepidation is explained as motions of the Earth. Second, the decreasing solar eccentricity (Copernicus' second anomaly of the tropical year) is mirrored by comparable

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[9] Barker and Goldstein, "Patronage and the Production of *De revolutionibus*."

[10] A few historians have observed that the *Narratio* rivaled or exceeded *De revolutionibus* as a source of information on Copernicus' work, including Thomas S. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought* (Cambridge: Harvard University Press, 1957), 186; and Marie Boas Hall, *The Scientific Renaissance*, but omit any detailed examination of its contents. For evidence for continued attention to the *Narratio*, see Tredwell "Maestlin and the Fate of the *Narratio*."

[11] *NP*, fol. C3r-C4v.

reductions in planetary eccentricities. By implication, a single change in the Earth's motion would be distributed equally through all celestial appearances.

Third, the centers of the deferents of the five planets are near the Sun, making it the most fit location for the center of the universe. Here it is important to know that Copernicus distinguished between the center of planetary motions and the visible solar body. The first is the *mean Sun*, a tool of calculation; the second is the *true Sun*, the physical object we see in the heavens. The true Sun is slightly removed from the center of planetary deferents, but Copernicus never indicated whether he believed the true Sun to be the true center of the world. Rheticus likewise leaves the question open with an ambiguous statement that could put either the true or mean Sun at the center.

In the third category Rheticus includes several phenomena that support heliocentrism. The bounded elongations of Venus and Mercury can be explained by a form of geoheliocentrism. Martianus Capella was one of the primary authorities for heliocentrism of the inferior planets, but Rheticus surprisingly ascribes the idea to Pliny, whose confused account of the heavens assumed the Earth as the center of all planetary motions.[12] Another example is the parallax of Mars, which is sometimes greater than the Sun according to Rheticus. From this it follows that the Earth cannot be at the center of the cosmos. In all the superior planets but especially in Mars, the planet is brightest at evening rising when it is in opposition, but dimmest at morning rising when it nears conjunction with the Sun. It follows that Mars is nearest to the Earth at opposition but farthest at conjunction. By implication, only heliocentrism can explain the great change in brightness, because the radius of the epicycle cannot be so great that it brings Mars

[12] Pliny, *Natural History* 2.14 (2.17 in Rheticus' annotation)

nearer than the Sun.

The single sentence Rheticus devoted to his second observation has proven to be problematic in both sixteenth-century scholarship and modern historiography. He asserts, without report of observation and without clear attribution, that the parallax of Mars sometimes exceeds that of the Sun. In a heliocentric system, this would only be possible at opposition and would be difficult to detect. Aristarchus' complicated method of determining the Sun's distance was necessitated by the minuteness of solar parallax. No record survives of Copernicus making such an observation, which would have been impossible in any event given the limits of his instrumentation.

A curious "verification" of this claim was produced later in the century by Tycho, who may be reckoned among the most gifted naked-eye observers known. A staunch opponent of terrestrial motion, Tycho initially reported that Mars exhibited no parallax. Later he proposed a fully geoheliocentric system, which also predicted that Mars would sometimes approach nearer the Earth than would the Sun. In a letter to Peucer, he reported having found a relatively large Martian parallax. His claim convinced Maestlin, who cited it in support of this very passage from Rheticus, only to withdraw his support after Kepler published an allegation that the "observation" derived from the mistaken calculation of one of Tycho's assistants. Dreyer discredited Kepler's explanation in turn when he found that the work had also been done in Tycho's own hand, but the origin of Rheticus' statement remains a mystery.[13]

The fourth reason for discarding ancient hypotheses is that Copernicus preserves

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[13] Dreyer, *Tycho Brahe* (Edinburgh: A. and C. Black, 1890); Owen Gingerich and James R. Voelkel, "Tycho Brahe's Copernican Campaign," *JHA* 29 (1998): 1-34. For an attempted reconstruction of Brahe's method see Goldstein and Barker, "The Role of Rothmann in the Dissolution of the Celestial Spheres," *British Journal for the History of Science* 28 (1995): 385-403. Maestlin's acceptance and subsequent

the principle of uniform motion about a circle's own center, a reference to the elimination of the equant already mentioned in the context of lunar theory. Its inclusion in this list implies that only a heliocentric system avoids the problem of the equant device, even though the same method could be transferred to geocentric models (as would be done by Reinhold and other mathematicians). Fifth, in explaining several apparent motions by the motion of the Earth alone, Copernicus has followed the principle of economy laid down by Galen, that a single thing in nature may create several effects. The motion of the Earth allows for a motionless Sun and sphere of fixed stars, eliminating the need for invisible outer spheres. It also minimizes the number of orbs needed for the models of the five planets because it accounts for a variety of motions, including motion in latitude.

Rheticus devotes the most space to the last advantage of heliocentrism, namely the harmony it creates throughout the entire system. When referred to a stationary Earth, the motions of all planets include as one element the mean motion of the Sun. Ptolemaic astronomy provides what we would call *ad hoc* explanations for this phenomenon. The radii of the epicycles of superior planets remain parallel with a line drawn from the Earth to the mean Sun. Each epicycle completes its period in a year and each planet retrogrades when it is in opposition to the Sun. In the case of Venus and Mercury, on the other hand, radii drawn to the center of the epicycles remain aligned with the mean Sun (figure 17). Each planet completes its deferent motion in a year. The Ptolemaic models allowed astronomers to predict planetary positions and to give accounts of *how* their motions occurred, but nobody could explain *why* the motions were harmonious.

As Rheticus observes, heliocentrism gives a more satisfying account of the

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rejection of Tycho's claim are discussed in Tredwell, "Maestlin and the *Narratio*," 315-16.

phenomenon of solar rule. The actual motion of the Earth manifests as apparent motion in the Sun and the other planets, yet the relative positions of the celestial bodies determine how that motion makes its appearance. He calls previous astronomers to task for not searching out such an explanation. Like musicians, they ought to have created harmony by tuning a whole instrument to a single string. According to Copernicus, the entire system of celestial bodies is attuned to the Sun as dancers follow a choral leader. In astronomy, the Sun governs the planets as a monarch, an extension of a familiar cosmological image. Rheticus describes two alternate applications of the regal analogy. The Sun may govern by wandering through the heavens like a royal procession, in accordance with geocentrism; or it may rule from the center, as an emperor who remains in one place rather than traveling through every city he rules. He also likens the heliocentric Sun to the heart, which sustains life throughout the organism without itself moving. The Earth's eccentric motion, which is the "efficient cause" of the Sun's mean motion, calls for the replacement of the entire system. Rheticus ends his most sustained defense of heliocentrism with an allusion to unidentified ancient praises of the Sun, which in the absence of the new cosmology had been overlooked as being purely poetic.

The enthusiasm Rheticus shows for the doctrine of his new teacher reflects Copernicus' potential success in overcoming the longstanding problem of certainty in astronomy. Mathematics held the potential to provide certain knowledge, for a sound geometrical proof is irrefutable. Yet in many instances it provides equally likely alternatives concerning the composition of the world. The classic example in astronomy is Apollonius' theorem, which demonstrates that an epicycle on concentric assigned appropriate parameters generates the same motion as an eccentric. Another example is the ordering of the planets: as we saw in chapter three, an interchange of the positions of Saturn and Jupiter does not affect the planetary positions predicted by Ptolemaic models. The radius of the epicycle is determined by the radius of the deferent; if the size of the deferent is changed, the epicycle is scaled accordingly and retrogradations appear to span the same angular distance.[14]

Astronomers inevitably dealt with uncertainty on a practical level, even though the true system of celestial orbs was theoretically knowable, by adopting one set of orbs for each planetary model and proceeding with their calculations. Assigning an eccentric to the Sun gave one possible account of the phenomena, but the alternative of an epicycle-on-concentric could not be eliminated. Furthermore, mathematics occupied a low position in the Aristotelian hierarchy of the sciences because it could not provide the same level of causal knowledge accessible through physics. Rheticus was aware of the limits of his profession, yet he had learned from Melanchthon to regard astronomy as one of the clearest examples of divine providence. The orderliness and predictability of the heavens demonstrated that the world had been created by a God who cared for and governed his creation.[15]

In the eyes of Rheticus, Copernicus offered a new level of mathematical certainty about the heavens and new insight into God's providence. He had still not resolved the difficulty of Apollonius' theorem. The planetary theories, like the solar theory, could be represented by any of three interchangeable sets of orbs. Nevertheless, accepting heliocentrism allows the mathematician to reveal the true causes of celestial appearances.

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[14] On the problems of demonstration in astronomy see Barker and Goldstein, "Realism and Instrumentalism."

[15] Kusukawa, *Transformation of Natural Philosophy*; and Barker, "Role of Religion."

Rheticus reminds his reader of the importance of causal explanation with a reference to Aristotle's *Metaphysics*: "Aristotle says, that thing is most true which is a cause for posterior things to be true."[16] He explains that because mathematical astronomy can now reveal the causes of observed phenomena, it can sometimes offer knowledge superior even to that provided by physicists. According to a classic syllogism, we know that the stars are distant because they twinkle. But we know it more surely from the Copernican hypotheses, he says, because the great orb is tiny in comparison to the sphere of fixed stars. The motion of the Earth causes no perceptible change in the position or size of the stars; therefore, they must be extraordinarily far away.[17]

The *Narratio* identifies several examples of Copernicus' success in explaining the causes of difficult phenomena, including the bounded elongation of the inferior planets, the Sun-linked retrogradation of the superior planets, and the fixed ordering of the planets. Rheticus reserves some of his highest praise for the discovery of a hidden order that emerges from the apparent chaos of the planetary models:

> What is more, all these things show themselves to be connected amongst themselves most beautifully as if by a golden chain. And any of the planets, in its position, and its order, and the diversity of its every motion, gives evidence that the earth moves, and that according to the turning about of the globe of the earth, to which we cling in place, we believe that by various ways they wander about in

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[16] "Aristoteles, inquit, Verissimum est id, quod *posterioribus*, vt vera sint, causa est." *NP* (1540), fol. D1v. A modern translation of the passage from which Rheticus quotes reads, "Now we do not know a truth without its cause; and a thing has a quality in a higher degree than other things if in virtue of it the similar quality belongs to the other things as well (e.g. fire is the hottest of things; for it is the cause of the heat of all other things); so that *that which causes derivative truths to be true is most true*." (My emphasis. Note that this translation obscures the technical term "posterior.") Aristotle, *Metaphysics* 2.1, from *The Basic Works of Aristotle*, ed. Richard McKeon (New York: Random House, 1941), 712-713 (transl. W. D. Ross).

[17] *NP* (1540), fol. D2r. Compare Aristotle, *Posterior Analytics* 1.13. The syllogism Rheticus describes is of the *quia* or "knowledge of the fact," variety, i.e., it derives causes from effects. Aristotle's example actually uses non-twinkling to demonstrate the nearness of planets, but the terms of the syllogism can be modified, as here, to prove that twinkling objects are distant. Note that Rheticus presents the great size of the sphere of fixed stars as a strength for heliocentrism, whereas most contemporaries regarded it as a disadvantage.

their own motions.[18]

But mathematics alone can only carry knowledge to a certain point. In an elaborate analogy leading up to the "golden chain" passage, Rheticus compares the mathematician to a blind man wandering about with only a staff to find his way. Eventually he learns that he cannot continue with only the staff to guide him.

> Now further when at last he has lost heart, God having pity stretches out his own hand, and with his hand leads [him] to the desired end. The Astronomer's Staff is that very Mathematics or Geometry with which he dares to test and enter upon the road at first. For what indeed [is] the strength of human intelligence in searching for these divine things, so far separated from us that the eyes darken?[19]

The mathematical disciplines prepare the mind to understand astronomy, so Melanchthon's educational reforms serve a purpose, but the final step must be taken intuitively. Rheticus is vague on how the process works, save that it involves divine intervention, but it relies on a pre-existent knowledge of mathematics already inscribed on the human soul. Elsewhere he explains that the mind is similar to the heavens and can therefore understand more quickly than the voice, just as one is able to grasp a demonstration more quickly than it can be explained. The concept echoes Melanchthon's doctrine of the "natural light" by which we are able to recognize indisputable truths, including mathematical truths and the rightness of moral law.[20]

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[18] "Adeo omnia haec tanquam aurea catena, inter se pulcherrime colligata esse apparent & planetarum quilibet, sua in positione, suoque ordine, & omni motus sui diuersitate, terram moueri testatur, & nos pro diuerso globi terrae, cui adhaeremus situ, credere diuersimodis eos motibus proprijs diuagari." *NP* (1540), fol. F2r (my translation).

[19] "Porro iamiam animum despondenti, ipsius misertus Deus manum porritig, manuque ad optatam metam perducit. Baculus Astronomi est ipsa Mathematica seu Geometria, qua viam tentare et insistere primum audet. Quid etenim humani ingenij vires ad diuinas has res, tamque à nobis dissitas procul, inuestigandas, quàm caligantes oculi?" *NP*, fol. F1v (my translation).

[20] *NP* (1540), fol. D2v. On the use of the natural light by Melanchthon and Kepler, see Barker, "Kepler's Epistemology," in *Method and Order in Renaissance Philosophy of Nature*, ed. Daniel A. DiLiscia, Eckhard Kessler, and Charlotte Methuen (Aldershot: Ashgate, 1997), 355-360.

Several passages in the *Narratio* contain ideas deviating sharply from what we find in Copernicus' astronomical writings. Some historians have suggested that he shared these ideas with Rheticus but considered them inappropriate for *De revolutionibus*. It is equally and perhaps more likely that they reflect the student's interpretation of his teacher's doctrine. One such idea is the "staff of the astronomer" discussed above, which resembles Melanchthon's epistemology; another is the "monarchies of the world," which is frequently pointed out in modern scholarship as a variation from *De revolutionibus*. The monarchies passage has drawn attention because it appears to give an astrological interpretation of Copernican astronomy.[21]

Following the exposition of the motion of the solar apogee, Copernicus' first and second inequalities of the tropical year (presented as part of the Sun's motion, since Rheticus has not yet revealed the new cosmology), the *Narratio* has a section titled "The monarchies of the world change with the motion of the eccentric," the relevant part of which is translated in appendix 4. According to Copernicus the center of the eccentric is moved on a small circle over a period of 3,434 Egyptian years. As a result the center of the eccentric approaches and then recedes from the center of the world and the eccentricity of the Earth's orb changes. Rheticus observes that the entrance of the center of the eccentric into a new quadrant has always been accompanied by some great change in world government. When the eccentricity was at maximum around 60 BCE, Rome changed from a republic to a monarchy, only to crumble and fall in step with the

[21] There is no consensus on the source of the "monarchies" passage. Rosen, *Three Copernican Treatises*, 122-23 n. 57, whiggishly assumes that the passage must be original to Rheticus, since Copernicus did not believe in anything so superstitious as astrology. Thorndike, *History of Magic*, 5:419, allows that the idea may have originated with either astronomer. Dreyer, *History of Astronomy*, 333, assumes that Rheticus follows Copernicus slavishly. I argue below that it is substantially original to Rheticus.

diminishing eccentricity.[22] When the eccentricity had moved through a quarter of the circle (a period of 858 1/2 years), Islam arose and became a flourishing empire in turn. Rheticus predicts that it will fall in another century, when the eccentricity reached its minimum, and that Christ will return after another quarter of the circle. At that time the eccentricity would have again reached its mean and would be increasing, which was its situation at the creation of the world.

In summary, Rheticus uncovers in the Copernican model of the motion of the apogee an indication that secular time will end about six thousand years after creation. Kraai has demonstrated that a prophecy to this effect was taught at Wittenberg through the *Chronicle Carionis*, a history book heavily revised by Melanchthon.[23] Rheticus follows the common tradition of attributing the prediction of a six-thousand year history to Elijah. In its fully developed form, the prophecy occurs nowhere in the canonical books of the Bible, and the earliest known reference occurs in the *Babylonian Talmud*. Its roots can be found in the Bible, however, in passages from the Old and New Testaments.[24] Melanchthon includes the prophecy in his oration *On Orion*:

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[22] According to Kraai, "Rheticus' Heliocentric Providence," 92, Rheticus diverges from Copernicus at this point by placing the beginning of the cycle at 60 BCE, as opposed to 64 BCE as given in *De rev* (1543), 3.21, fol. 92r. But Rheticus, *NP* (1540), fol. B1r writes "Ante natiuitatem Domini LX ferè annis erat maxima eccentricitas." The key word *fere*--also used by Copernicus--means "nearly."

[23] Kraai, "Rheticus' Heliocentric Providence," 91-98. Kraai's exposition of the Copernican motion of the Earth in the same section contains several errors: He confuses the second inequality of the tropical year (the motion of the center of the Earth's deferent on the "small circle") with the anomaly of obliquity (one of the librations of the poles), probably because both have a period of 3,434 Egyptian years. He confuses the motion of the Earth's apogee around the Sun (an element of the first inequality) with the precession of the equinoxes (part of the third motion), although one has a period of 25,816 years and the other has a period of about 53,000 years. He wrongly identifies the motions of the eccentric as epicycles, perhaps because they can be represented schematically as overlapping circles. Finally, he believes that the purely explanatory circle of unequal motion, used to illustrate the variation in precession caused by the librations, is a real object in the heavens.

[24] "For a thousand years in thy sight are but as yesterday when it is past" (Psalms 90:4); ". . . one day is with the Lord as a thousand years, and a thousand years as one day" (II Peter 3:8). Wallis, in Bede, *Reckoning of Time*, 359-60, identifies these verses as the inspiration of the popular tradition.

> And the maxim which is ascribed to Elijah ought not to be despised: Six thousand years the World, and afterwards conflagration. Two thousand, Idleness. Two thousand, Law. Two thousand the time of the Messiah. And if somehow the years go astray, they stray because of our sins which are many.[25]

The last sentence of Melanchthon's version of the prophecy allows for deviation from a strict six-thousand-year limit, which is necessary for Rheticus to accommodate the chronology to Copernicus' cycle of 3,434 Egyptian years.

Past interpretations of the "monarchies" passage have approached it narrowly as astrology. It is true that Rheticus concludes with the hope that through the astrological study of great conjunctions (conjunctions of Jupiter and Saturn) and other phenomena Schöner will discover the nature of future empires. But the passage shows clear affinities with time-reckoning as well. Melanchthon's preface to the *Computus* identifies Rheticus as a promoter of the art; it also lists "the changes of empires" among the reasons to study time-reckoning. History and the ages of the world formed a standard part of the reckoning of time as much as the divisions of the day, month, and year. Bede devoted considerable attention to past and future history in his highly influential *De ratione temporum*. He divided past and present time into six ages, to be followed by the seventh and eighth ages as sacred time. He also mentioned the belief of some people that the world will last six thousand years, though he ridiculed the idea and assigned unequal lengths to past ages. Sacrobosco was silent about the number of ages the world would endure, but he did mention thousand-year ages of the world as part of the knowledge of

[25] "Et non contemnenda est sentential, quae Eliae tribuitur: Sex millia annorum Mundus, et postea conflagratio. Duo millia, Inane. Duo millia, Lex. Duo millia dies Messiae. Et si qui anni deerunt, deerunt propter nostra peccata quae multa sunt." *CR* 12:49. Nearly identical wording appears in a later edition of the *Chronicon Carionis*, *CR* 12:717, a book on world history written by the mathematician Johannes Carion (1499-1538) and revised by Melanchthon.

computus.[26] Seen in this light, Rheticus' passage on the monarchies of the world becomes a creative application of an established science linking history and the motions of celestial bodies. The "Wheel of Fortune," as he calls the circular motion of the apogee, is a marker of time that relates to changes in monarchies in the same way that the Sun and Moon relate to Easter.

Rheticus returned to his teaching duties in Wittenberg in the fall of 1541, taking with him a copy of the trigonometrical chapters from *De revolutionibus*. The following June they were published as *De lateribus et angulis triangulorum*, together with a table of sines prepared by Rheticus.[27] Rheticus had already left Wittenberg, however, and by May he had returned to Nuremberg with a copy of *De revolutionibus*. Petreius soon began printing the book, with Rheticus correcting the proofs. In October, however, Rheticus left for a new teaching position in Leipzig, leaving the task of supervising the publication to the Lutheran theologian Andreas Osiander (1498-1552). In a letter written on April 20, 1541, replying to a question now lost, Osiander advised Rheticus that "the peripatetics [Aristotelian philosophers] and theologians will be easily placated" if they are told that the book presents the models as computational devices but not necessarily representations of physical reality. Osiander's approach accorded with the prevailing view of astronomy, which denied it the certainty granted to physics.[28]

When *De revolutionibus* finally appeared in print, by May 21, 1543, it included a

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[26] Bede, *Reckoning of Time*, 157-249; Sacrobosco, *Computus* (1550), fol. Q1v.

[27] Copernicus, *De lateribus et angulis triangulorum* (Wittenberg: Johannes Lufft, 1542). For the motivation behind this publication see Barker and Goldstein, "Patronage and the Production of *De revolutionibus*."

[28] ". . . Peripathetici et theologi facile placabuntur, si audierint, eiusdem apparentis motus varias esse posse hypotheses. . . ." In Burmeister, *Rhetikus*, 3:25 (my translation). For analysis see Barker and Goldstein, "Realism and Instrumentalism."

disclaimer of the sort Osiander had recommended to Rheticus. The theologian had written a note addressed to the reader and added it anonymously, without consulting either Copernicus or Rheticus. Copernicus died on May 24 and so never had the opportunity to take steps to correct the situation. For a time Rheticus considered a suit to force Petreius to reprint the book without the preface. Eventually he abandoned the idea, though he had the opportunity to express his disapproval by striking out the preface in presentation copies. As a result, *De revolutionibus* went forth into the world with an unsigned letter that some readers believed to be a statement of intent by the author himself. [29]

In a letter of July 26, 1543, Tiedemann Giese, who had urged Copernicus to publish, mentioned a book by Rheticus reconciling the motion of the Earth with scripture.[30] Rheticus' apologetical tract was considered to be lost and probably destroyed until 1984, when Hooykaas translated and published a document he believed to be the missing treatise.[31] The document was an anonymous pamphlet published in the Netherlands during the seventeenth century as part of a debate over the incompatibility of Cartesianism and Copernicanism with scripture. After determining that all of the sources cited were available as early as 1532, Hooykaas argued that the text had a lack of confessional distinctiveness that would have been possible only in the earlier stages of

[29] We catch an indirect glimpse of one such incident in Giordano Bruno's (1548-1600) fictionalized retelling of his debate with the Oxford dons in *The Ash Wednesday Supper*, in which one of Bruno's first tasks is to undermine the Oxonian belief that Copernicus is the author of the letter. Hilary Gatti, *Giordano Bruno and Renaissance Science* (Ithaca: Cornell University Press, 1999), 55 n. 24, identifies Bruno as the first to issue a public rejection of Copernicus' authorship of the letter, though Bruno did not try to identify the author.

[30] Burmeister, *Rhetikus*, 3:54-59.

[31] R. Hooykaas, *G. J. Rheticus' Treatise on Holy Scripture and the Motion of the Earth* (Amsterdam: North Holland, 1984).

the Reformation. He concluded, further, that of all the possible supporters of Copernicus in that period, only Rheticus and Giese were known to have written a work on heliocentrism and biblical exegesis, and only Rheticus would have spoken of his "teacher" advocating terrestrial motion, since Giese was never in such a relationship with the astronomer. We should also consider that as a patron of Copernicus, Tiedemann Giese would not have described his client as a superior.

So far Hooykaas' identification of the treatise has not been refuted publicly, but neither has it been employed to any great extent in analysis of Rheticus. To date, only two authors have given serious attention to the treatise: Kraai, in the dissertation "Rheticus' Heliocentric Providence," and Kenneth Howell, in *God's Two Books*. Both authors accept Hooykaas' identification of the treatise without critical discussion and without adducing further evidence to support Rheticus' authorship. Both use the text as a starting-point for the investigation of his exegetical technique instead of testing it against known features of Melanchthon's approach to scripture.[32]

Since Hooykaas published the treatise, however, significant research has been done on the connections between Lutheranism and astronomy, beginning with Kusukawa's study of Melanchthon. Today, it would be surprising to find a theologically indistinct tract written by a Wittenberg-trained astronomer. Melanchthon himself had a set of stock images on which he drew whenever he wrote on astronomy: celestial motions as a manifestation of God's providence, sometimes in parallel with moral law; the protestation that the heavens cannot exist in vain; astronomy as a discipline founded by God; the contribution of astronomy to religious history and public life; and rhetorical

[32] Kraai, "Rheticus' Heliocentric Providence," 119-32; Howell, *God's Two Books*.

attacks on Epicureans or literary figures who denied divine providence, such as the Cyclops of the *Iliad*. These themes surface also in the writings of other members of the Melanchthon circle. Rheticus must have written the tract alluded to at an early date, when he would have been most likely to draw on intellectual resources he acquired at Wittenberg in order to mount a religious defense of an astronomical subject. Yet none of the themes appears in Hooykaas' document. I shall not attempt to answer the question of the authorship of the *Treatise on Holy Scripture* in this dissertation; however, the lack of provenance for the work, combined with the absence of clear Philippist traits, argue against ready acceptance of Hooykaas' identification of Rheticus as the author. A comparison of the *Treatise on Holy Scripture* with the *Narratio prima* and with Melanchthon's writings should precede any attempt to derive new information about Rheticus' theology from the treatise.

The early reception in Wittenberg

In the next chapter I consider the reaction to Copernicus on the part of mathematicians; for now, I shall restrict my discussion to possible responses on the part of people lacking the training to appreciate or critique Copernican mathematical arguments. The first is a famous episode that may in fact have been a non-incident. The *Tischreden* or "Table Talks" of Martin Luther are reports of conversations with Luther, written down by his companions and collected for publication after his death. As Luther did not share Melanchthon's passion for the study of nature, astronomy rarely figured as the topic of conversation over dinner. However, two witnesses, Anthony Lauterbach and Johannes Aurifaber, recorded slightly different versions of a conversation that took place on June 4, 1539. The Lauterbach version is considered to be the more reliable:

> There was mention of a certain new astrologer who wanted to prove that the earth moves and not the sky, the sun and the moon; This would be as if somebody were riding on a cart or in a ship and imagined that he was standing still while the earth and the trees were moving. [Luther remarked] "So it goes now. Whoever wants to be clever must agree with nothing that others esteem. He must do something of his own. This is what that fellow does who wishes to turn the whole of astronomy upside down. Even in these things that are thrown into disorder I believe the Holy Scriptures. For Joshua commanded the sun to stand still and not the earth.[33]

A second version, more frequently quoted by modern authors, is preserved by Aurifaber:

> People gave ear to an upstart astrologer who strove to show that the earth revolves, not the heavens or the firmament, the Sun or the Moon. . . . This fool wishes to reverse the entire science of astronomy: but sacred scripture tells us that Joshua commanded the Sun to stand still and not the Earth.[34]

Modern readers almost unanimously conclude, first, that Copernicus was the topic of

[33] No. 4638, Lauterbach version. Luther, *Luther's Works, American Edition*, ed. H. T. Lehman, ed. and transl. T. G. Tappert (Philadelphia: Fortress Press, 1967), 54:358-39. The preference for the Lauterbach version of this conversation is argued in John Dillenberger, *Protestant Thought and Natural Science: A Historical Interpretation* (Garden City: Doubleday, 1960), 37. The scriptural reference is to Joshua 10:12.

[34] Aurifaber version, translated in Andrew Dickson White, *A History of the Warfare of Science with Theology in Christendom*, 2 vols. (New York: D. Appleton, 1896), 1:126.

conversation, and second, that Luther's reaction represents the definitive Lutheran reaction to Copernicus.[35] Both conclusions are problematic.

The identity of the "astrologer" is far from certain. The brief reports in the *Table Talks* mention no characteristics unique to heliocentrism. We do not learn, for instance, that the astrologer puts the Sun in the center of the world or that he made the Earth a planet, only that he assigned some motion to the Earth that others attributed to the Sun, the Moon, and one or more other celestial spheres. (Given the lack of uniformity in numbering and naming celestial spheres, we cannot be sure what the speaker or writer meant by "sky," "firmament," or "heavens," but they probably refer either to the entire celestial realm or to the uppermost spheres.) Thus, the speaker could have had in mind a system which retained terrestrial centrality but posited a daily rotation of the Earth instead of the celestial spheres. Two fourteenth-century professors at Paris, Jean Buridan and Nicole Oresme, presented arguments for a rotating Earth--though Oresme concluded with a reversal stating that he had defended an absurdity as a logical exercise. Celio Calcagnini (1479-1541), a contemporary of Copernicus, also proposed a rotating central Earth in the treatise *Quod caelum stet, terra moveatur, commentatio, vel de perenni motu terrae*. In his own time Calcagnini was at least as well known as Copernicus. Much of the "evidence" for Copernicus' fame before 1540 amounts to the supposition that his work must have been widely known because it was known by a few--none of whom, however, were demonstrably in Wittenberg. In contrast, we can identify a direct connection

[35] Even Swerdlow and Neugebauer, *Mathematical Astronomy*, 21, report without qualification that Luther called Copernicus a *Narr*, i.e., a fool, showing that they followed the better known but less reliable Aurifaber version. Barker, "The Role of Religion in the Lutheran Response to Copernicus," in *Rethinking the Scientific Revolution*, ed. Margaret J. Osler (Cambridge: Cambridge University Press, 2000), 63, identifies A. D. White's *Warfare of Science with Theology* as a significant intermediary in the dissemination of the Aurifaber report.

between Calcagnini and Wittenberg through his correspondence with Ziegler.[36]

Assuming for the sake of argument that the astrologer is indeed Copernicus, Luther must have reacted on the basis of a lack of information. The conversation could have begun with a letter from Rheticus reporting that he was on his way to or else had just arrived at the home of Copernicus. The timing almost requires that he sent the note *before* reaching Frauenberg: on May 14 he was still in Poznan; the famous conversation took place on June 4, just over three weeks later. It would be optimistic to say even that Rheticus had begun his studies with Copernicus when he wrote the hypothetical letter to Wittenberg.[37] Certainly he could not have written home with an explanation of the wonderful conclusions that followed from accepting heliocentrism, and Luther, who lacked Rheticus' mathematical training, could not have imagined them on his own. He would have had no reason to assume that the young mathematician had uncovered anything more than another Calcagnini or Oresme, an ingenious novelty but without any meaningful difference from accepted cosmology.[38]

Moreover, Luther's comments should not be taken for an official statement of the Lutheran position on Copernicus. They are remarks made in the course of conversation and published without his approval. Discrepancies between the two accounts warn us not to trust the *Table Talks* as *verbatim* transcriptions; we should question, for instance,

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[36] Calcagnini, *Quod caelum stet, terra moveatur, commentatio, vel de perenni motu terrae*, in *Opera aliquot* (Basel: H. Frobenius and N. Episcopius, 1544), 388 ff. For Calcagnini's correspondence with Ziegler and on circulation of his treatise prior to its publication in 1544 see Barker, "The Lutheran Contribution to the Astronomical Revolution: Sicnece and Religion in the Sixteenth Century," ed. John Hedley Brooke, forthcoming.

[37] Barker, "Lutheran Contribution to the Astronomical Revolution."

[38] For an extreme version of this argument see Rosen, *Three Copernican Treatises*, 406-407. In a creative but highly unlikely interpretation of the *Table Talks*, Rosen suggests that Luther believed Copernicus to reject motion of the Moon in the same way that we know he rejected motion of the Sun, which would contradict even common sense.

whether he really called the astrologer a "fool." After Copernican astronomy became public knowledge with the publication of the *Narratio* in 1540 and *De revolutionibus* in 1543, Luther did not deem the matter sufficiently important to make a public statement. Most importantly, we must not confuse Luther with a modern pope making infallible statements *ex cathedra*. Luther was a respected leader of a new religious movement during his lifetime, but his words did not define all aspects of that movement. Although not himself drawn to find God's providence in natural philosophy, he tolerated Melanchthon's studies at Wittenberg as an acceptable approach to theology. The rigid insistence on the primacy of Luther's thoughts developed in the second half of the sixteenth century; it did not yet exist in 1539.[39]

What of Melanchthon, the "instructor of Germany"? Whereas his former student Rheticus had rushed to publish Copernicus' theories, Melanchthon's initial reaction was critical. The first edition of his textbook on natural philosophy, *Initia doctrinae physicae*, published in 1549, includes a section on the motion of the world critical of unnamed contemporaries who reject the daily rotation of the heavens.

> But some people either from love of novelty, or in order to show off cleverness, argue that the Earth moves, and they assert that neither the eighth sphere nor the Sun moves; although, indeed, they assign certain motions to the celestial orbs, still they place the Earth among the stars. And these games were not invented recently. . . . [T]o assert absurd opinions in public is not honest, and it hurts by example. It is of good mind to embrace reverently the truth shown by God and to be pleased with it, and to thank God for kindling some light and for watching over the minds of men; next to consider who may be brought to God through the light, and how life ought to be guided and aided by knowledge of truth.[40]

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[39] On the split in Lutheranism that developed after Luther's death, resulting in the suppression of Melanchthon's followers late in the century, see *The Oxford Encyclopedia of the Reformation*, ed. Hans J. Hillerbrand (New York: Oxford University Press, 1996), s.v. "Philippists."

[40] "Sed hic aliqui vel amore novitatis, vel ut ostentarent ingenia, disputarunt moveri terram, et contendunt nec octavam sphaeram, nec Solem moveri, cum quidem caeteris coelestibus orbibus motum tribuant, Terram etiam inter sidera collocant. Nec recens hi conficti sunt . . . Etsi autem artifices acuti multa exercendorum ingeniorum causa quaerunt, tamen adseverare palam absurdas sententias, non est honestum,

In this passage we can hear an echo of the concerns stirred up by the Anabaptists and projected by Melanchthon onto the Epicureans. Attributing motion to the Earth will cause trouble, but perceiving God's providential hand in nature will lead one to worship the true God. The remainder of the section adduces a mixture of scriptural quotations, physical arguments, and astronomical observations to prove that the Earth must be at rest in the center of the universe. In contrast to the vague reference in the *Table Talks*, Melanchthon's critique is without question directed against Copernicus, because he tells us that the lovers of novelty were anticipated by Aristarchus in making the Earth a star.

Like Luther's dinner-table comment, the passage has been quoted out of context to prove religiously motivated opposition to Copernicanism--and scientific advance of any sort--on the part of Melanchthon. Yet the first edition also praises the Copernican lunar model and adopts his values for several planetary apogees.[41] Before long he was to take a more favorable view of Copernican astronomy. Melanchthon first gave notice of his change of mind in an oration he wrote for Reinhold.

> Influenced by these and similar observations [e.g., the times of the equinoxes], we began to love and admire Copernicus more. . . . In which consideration we turn our minds to the true or apparent magnitude of the year [which] is once more greater than in the times of either al-Battani or Alfonso, and again made nearly equal to that which Ptolemy proclaimed, that is to say more than 365 days 5;55 hours. Since the return of the Sun to the middle of the equinoctial does not surpass 5;49,20 hours. And the return of the Sun to the same fixed star exceeds a fourth of a day by almost a sixth of an equinoctial hour [i.e., about 6;10 hours]. One may

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et nocet exemplo. Bonae mentis est veritatem a Deo monstratam reverenter amplecti, et in ea acquiescere, et Deo gratias agere, aliquam accendenti lucem, et servanti in hominum mentibus, ac deinde considerare, quis ad Deum aditus sit per eam lucem, et quomodo vita regenda et iuvanda sit agnitione veritatis." *CR* 13:216 (my translation).

[41] For examples of positive use of Copernicus in the 1549 edition see *CR* 13:244 (lunar model praised), 262 (Copernican apogees for superior planets); see also Westman, "Wittenberg Interpretation," 173.

name such a year *Asteroterida*.[42]

Written in 1549, this oration reveals not only the date of the re-evaluation of Copernicus at Wittenberg, but also that it was motivated by concern over the length of the year. Compare Melanchthon's figures with *De revolutionibus*: the *Asteroterida* year is the sidereal year of 365 d 6;9,40 h (the second motion); while the various year-lengths of past authorities approximate the mean tropical year of about 365 d 5;49,36 h (third motion).

In a second edition of the *Initia doctrinae physicae* published in 1550, Melanchthon amended the passage to moderate his criticism. The changes include striking out the phrases "either from love of novelty, or in order to show off cleverness" and "And these games were not invented recently"; replacing the verb "argue" (*contendunt*) with the milder "say" (*dicunt*); and rewriting the section critical of "assert[ing] absurd opinions" to read:

> . . . younger people ought to know not to want to assert those things strongly. However, in introductory education they should love received opinions which are least absurd, with the general consent of experts; and when they understand that the truth is shown by God, they should embrace it reverently, acquiesce to it, and thank God for kindling some light and watching over the human race.[43]

[42] "His et similibus observationibus moti, Copernicum magis admirari et amare coepimus. . . . In qua consideratione animadvertimus anni veram seu adparentem magnitudinem eius, quam Copernicus temporalem, Graeci *topikon*, Latini vertentem dicunt, nunc iterum maiorem esse, quam vel Albategnii vel Alphonsi temporibus: ac pene rursus aequalem factam ei, quam Ptolemaeus prodidit, videlicet praeter dies integros 365 horarum 5 et scrupulorum primorum 55 unius horae. Cum reditus Solis ad medium aequinoctium non superet horas 5 scrupula 49 cum triente unius scrupuli. At reditus Solis ad eandem stellam fixam excedit quadrantem diei pene sextante unius horae aequinoctialis. Quem annum licet *Asteroterida* nominare." *CR* 11:839 (my translation).

[43] ". . . tamen sciant iuniores non uelle cos talia adsuerare. Ament autem in primo institutione sententias receptas communi artificium consensu, quae minime sunt absurdae, & ubi intelligunt ueritatem á Deo monstratam esse, reuerenter eam amplectantur, acquiescant in ea, & Deo gratias agant aliquam accendenti lucem, & seruanti in genere humano. Deinde considerent. . . ." Melanchthon, *Initia doctrinae physicae Dictata in Academia Witebergensi Philip. Melanth. Iterum edita* (Wittenberg: Johannes Lufft, 1550), fol. 39v-40r. The remainder of the passage is identical Westman, "Wittenberg Interpretation," 173 n. 31, discusses the rediscovery of this change of mind. Peter Barker has drawn to my attention an error in his article "Role of Religion," 64: Melanchthon could not have made the changes to certain later editions of the *Initia doctrinae physicae*, which were published in 1562 and 1567 after his death.

The revisions show a moderating of Melanchthon's initial outburst against heliocentrism. While he still considers the Earth's motion to be an "absurd opinion," he has ceased viewing it as a clever game that should not be played in public. Young students should learn the traditional order, but he does not cut off the possibility that advanced students be exposed even to incorrect teachings. Probably, as I argue in chapter 5, the preparations were already being made for incorporating Copernican astronomy into the advanced curriculum.

I conclude this section by returning to the issue of Rheticus' status at Wittenberg. This chapter began with possible reasons for his departure for Nuremberg in 1539, including Kraai's suggestion that he virtually fled Wittenberg to avoid a scandal. Any threat to Rheticus on account of the scandal could not have been great or long-lasting because he returned to Wittenberg without incident to lecture on astronomy and to serve as dean of arts. Kraai attempts to marginalize the return of Rheticus as the bare minimum required of him by his agreement with the university. In his view, the young astronomer faced renewed hostility because of his advocacy of Copernicus. For instance, student notes calling him *Heliopolitanus*, or "he of the city of the Sun," are read by Kraai as strongly dismissive of Rheticus' enthusiasm.

The central piece of evidence in Kraai's argument comes from a letter written by Melanchthon to Camerarius in November 1542. Kraai translates the following passage from the letter:

> The question of Rheticus' stipend and work should be dealt with plainly and explicitly. *There are from him [Rheticus] there [in Wittenberg] predictions forecasting the captivity of Otus and Ephialtes*. All of these are intertwined in him when with us.[44]

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[44] "Cum Rhetico proderit plane et explicate de stipendio et operis agi. *exei gar kakeinos oroscopounta ton aixmaloton tou otou kai tou ephialtou*. Omnia ei apud nos integra sunt." *CR* 4:896, translated in Kraai,

The italicized sentence, which is the key to the argument, originally appeared in Greek. Kraai is correct that understanding the letter requires decoding the symbolism; the question is whether he has uncovered the intended meaning.

Otus and Ephialtes, also called the Aloides, were the twin sons of Poseidon in Greek myth. They grew prodigiously, and at the age of nine they attempted to overthrow Zeus by piling mountain upon mountain until they could reach the celestial abode of the gods. The Aloides failed and were killed. A series of similar encounters appear in Greek literature: the Titanomachy, a struggle between the Olympians and the Titans that ended with the securing of Zeus' supreme authority; and the Gigantomachy, a war between the established gods and monstrous giants. Both wars were part of a widespread and long-lived tradition of a rebellion by giant figures against the rightful authority of God or the gods, often with astral or astrological overtones.

Melanchthon invokes the theme of disruptive giants repeatedly in his writings on providence, but only rarely as the Aloides or the Titans. More frequently he compares deniers of providence to the Cyclops of Homer's *Odyssey*, an uncivilized brute who lived alone in a cave. Although he did not join in an organized rebellion, the Cyclops too refused to accept the authority of Zeus as his words to Odysseus reveal: "We Kyklopês care not a whistle for your thundering Zeus or all the gods in bliss; we have more force by far. I would not let you go for fear of Zeus--you or your friends--unless I had a whim to."[45] For Melanchthon, the Cyclops symbolized anyone who denied God's providence,

"Rheticus' Heliocentric Providence," 140 (bracketed words supplied by translator). I have interpolated Kraai's separate translation of the Greek.

[45] Translated in Homer, *The Odyssey*, transl. Robert Fitzgerald (New York: Vintage Classics, 1990), 9.298-302, p. 153.

including his provision for our well-being through the arts. In the preface to Peurbach's *Theoricae novae* he compares the Cyclops to someone who declares his savage nature by denying the signs of divine providence in celestial motions. The same passage calls Epicureans *theomachoi*, meaning that they struggle against God, because they deny the science of motions. In the *Oration on Astronomy and Geography*, both the inhospitable Cyclops and the giants piling mountain upon mountain represent those who do not recognize God's order manifest in the heavens.[46]

Why did Melanchthon introduce the Aloides into his letter to Camerarius? In Kraai's interpretation, they represent Rheticus himself. According to Kraai, the general opinion at Wittenberg was that Rheticus had audaciously tried to seize the heavenly realm like some new giant; consequent hostility had grown so intense that he feared imprisonment should he return there.[47] Such a reading contradicts the established symbolism that condemns giant figures for rejecting astronomy and the other liberal arts. Kraai would have us believe that Melanchthon has inverted the symbolism and made Rheticus a giant for pursuing astronomy--and what is more, Camerarius must be expected to recognize the reversal! Moreover, the final sentence does not say, as Kraai would have it, that Rheticus' behavior has somehow gotten "entwined" with giant tendencies. The adjective *integer* actually has meanings such as "perfected," "pure," or "finished," in the sense of wholeness. A literal translation might be: "All things are completed for him among us"; a more idiomatic rendering would be "All his accounts [or affairs] are settled

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[46] Melanchthon, *CR* 2:814-21 (*Theorica* preface); and *Orations on Philosophy and Education*, 115, 118 (*Oration*). Kraai accepts Rheticus, not Melanchthon, as the author of this narration, but my main point, that the identification of Cyclops with other rebels was current at Wittenberg, does not depend on exact authorship.

[47] Kraai, "Rheticus' Heliocentric Providence," 139-40.

[or squared] with us."[48] In other words, Rheticus has completed his obligations at Wittenberg and is free to seek employment elsewhere, a far less sinister message.

Melanchthon provides the signification for the Aloides in the letter itself. When giants are slain, the earth brings forth more giants from their blood. In the same way, he says, new sophists always emerge from the remains of the old, growing worse with each generation.[49] Kraai's reading requires that Melanchthon identify Rheticus not only with giants but also with argumentative sophists possessing the qualities of ambition, envy, and jealousy. A more natural reading is that Otus and Ephialtes are sophists mentioned by Rheticus in a letter. Far from facing his own imprisonment, Rheticus is contemplating the imminent arrest of some disruptive element and Melanchthon is learning about the trouble at a distance, just as Luther heard about the Zwickau prophets while in hiding.

[48] "Omnia ei apud nos integra sunt." I am grateful to Laura Gibbs for her suggestions regarding the more natural idiomatic translation.

[49] *CR* 4:895-896.

Conclusions

I shall reserve comments about Rheticus himself until the next chapter, when I can discuss him in the context of his fellow Lutheran mathematicians. It is appropriate, however, to draw some conclusions about the reaction to Copernicus at Wittenberg. Clearly neither Luther nor Melanchthon were receptive to talk about terrestrial motion, but neither grounded their objections in scripture alone. Luther condemns the astrologer, whoever it is, in part for reversing the art of astronomy, meaning either that he has shifted the principles of the art or that he has put it above physics. In the context of physics, Melanchthon emphasized the observational and physical counterarguments while giving very little time to scriptural problems. There is no evidence showing that Rheticus was in real danger for promoting Copernicus. Paradoxically, his teacher and supporter Melanchthon produced the harshest surviving criticisms of heliocentrism in the *Initia doctrinae physicae*, though he soon softened them when he came to see that Copernicus might also benefit astronomy. Apparently he did not see his student as a locus of disorder.

CHAPTER 5

THE WITTENBERG TRADITION IN GERMANY

Rheticus' colleagues and successors at Wittenberg took a moderate approach to *De revolutionibus*. Like Melanchthon, they incorporated what they saw as improvements on existing Ptolemaic astronomy so long as changes could be expressed in geocentric terms, but declined to adopt the new cosmology and its concomitant physical problems. Most of the early promoters of Copernicus across Europe, in fact, expressed no enthusiasm for what moderns usually consider to be his great contribution, even where they did not attack heliocentrism openly. The Wittenberg Interpretation of Copernicus, a concept first introduced by Robert Westman, has proven to be a fruitful interpretation for historians of astronomy who need to balance the widespread use of Copernican astronomy for calculating planetary positions with continued preference for geocentrism.[1] Yet the Wittenberg Interpretation has so far remained unique as an institutionalized tradition. Nobody has described a Paris Interpretation or a Vienna Interpretation, though it is highly probable that astronomers outside Wittenberg not only read Copernicus geocentrically but taught the approach to their students.

Erasmus Reinhold and Caspar Peucer, the first two astronomers I discuss in this chapter, are the main representatives of the Wittenberg Interpretation. Reinhold spoke

[1] The classic description of the Wittenberg Interpretation is in Westman, "Melanchthon Circle."

favorably of Copernican models, but he neither criticized nor praised heliocentrism expressly in his surviving writings. Peucer, his student and successor, openly attacked the cosmology of *De revolutionibus* but preferred select elements of its astronomy. Michael Maestlin, the third astronomer, represents a new generation of mathematicians trained in the Wittenberg tradition and dispersed through the regions dominated by Lutheranism. Maestlin became a Copernican early in life and claimed that mathematics demonstrated that the Earth revolves around the Sun, not vice versa. At the same time his work continued in the tradition established by earlier astronomers at Wittenberg.

This chapter traces the Lutheran reform of astronomy through the writings of Reinhold, Peucer, and Maestlin. The publication of *De revolutionibus* took the reform in an unexpected direction leading to the establishment and transformation of the Wittenberg Interpretation of Copernicus. Part of my goal in this chapter is to contextualize the famous Interpretation by investigating what these astronomers approved of in the new astronomy and what they saw as problematic. It should be remembered also that all three were familiar with Melanchthon's religious approach to astronomy and repeated its main tenets in some form in their own work. In the next two chapters I shall consider to what extent their works, along with Melanchthon's own writings, influenced English astronomy by making available both the astronomical content of their teachings and their providential reading of the celestial realm.

Erasmus Reinhold (1511-1553)

The life of Erasmus Reinhold is more obscure than that of his colleague Rheticus, although we know more about him than about the shadowy Sacrobosco.[2] He was born in Saalfeld, Germany, and was a student at Wittenberg by 1530, the year before the publication of the *Sphaera* preface signaled new importance for astronomical studies at the university. In May of 1536 he was appointed professor of higher mathematics at Wittenberg by his mentor Melanchthon, coincidentally the same year as the appointment of Rheticus to the chair of lower mathematics. In 1552 he left Wittenberg during an outbreak of plague, but died the following year in his home town of Saalfeld. We know him primarily through his astronomical writings, most of which he wrote as textbooks for his lectures at Wittenberg.

Reinhold's duties included lecturing on Peurbach's *Theoricae novae*. The book already had an established place in the curriculum; Melanchthon recommended it in the *Sphaera* preface in 1531 and wrote a preface to Peurbach in 1535.[3] When Reinhold took up the chair of higher mathematics, he prepared extensive commentaries on the *Theoricae novae* that were published in 1542, along with Melanchthon's old preface and new prefatory material. He began revising his commentary in the following years but was prevented from finishing the project by his early death. His student and successor Caspar Peucer collected Reinhold's notes for a new edition of the commentary on Peurbach, published in 1553; the changes are limited to slight modifications to the preface and a

[2] For biographical information on Reinhold, see *DSB* 11:365-67; and Barker, "Reinhold, Erasmus," in *Encyclopedia of the Scientific Revolution from Copernicus to Newton*, ed. Wilbur Applebaum (New York: Garland, 2000), 560-61.

[3] Melanchthon, *Orations*, 108 (Peurbach's *Theorica* praised); and *CR* 2: 814-21 (*Theorica* preface).

revised commentary on the solar model. (Peucer's explanation is translated at the end of appendix 5.) Both editions were reprinted frequently in the sixteenth century.[4]

After 1543 Reinhold devoted much of his time to *De revolutionibus*. In 1551 he published the first set of astronomical tables based on Copernican models. The *Prutenic Tables*--so called in honor of Reinhold's patron the Duke of Prussia, as well as of Copernicus' homeland--competed successfully with the medieval *Alfonsine Tables* until they were rendered obsolete in turn by Kepler's *Rudolphine Tables* in the seventeenth century. The *Prutenic Tables* helped to promote the fame of Copernicus among the mathematicians of Europe, in part because they meant that his name became associated with that of Reinhold, who had gained some repute as a competent astronomer before his early death. Having a set of tables also meant that astronomers could make predictions from Copernican models without being forced to extract the information buried in *De revolutionibus*. By Reinhold's own report he calculated them entirely anew from Copernicus' observations. Modern studies confirm that he corrected a number of errors in calculation in *De revolutionibus*. Since Copernicus derived his models from relatively few observations, actual improvements in accuracy provided by the *Prutenic Tables* were modest or nonexistent. However, contemporaries perceived Reinhold's tables as better than the *Alfonsine Tables* and as a significant contribution to the reform of astronomy.[5]

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[4] Peurbach, *Theoricae novae planetarum Georgii Purbacchii, Germani, ab Erasmo Reinholdo Salveldensi ... Inserta item methodica tractatio de illuminatione Lunae. Typus Eclipsis solis futurae anno 1544* (Wittenberg: Lufft, 1542); Peurbach, *Theoricae novae planetarum Georgii Purbacchii, Germani, ab Erasmo Reinhold Salveldensi... Recens editae & auctae novis scholiis in Theoria Solis ab ipso autore* (Wittenberg: Lufft, 1553). For a detailed comparison of the two versions of the commentary on the Sun, see Tredwell, "Reinhold's Response to Copernicus: Copernican Solar Theory in Erasmus Reinhold's Commentary on Peurbach's *Theoricae novae planetarum*" (M.A. thesis, University of Oklahoma, 1999).

[5] For the accuracy of the *Prutenic Tables* and of ephemerides derived from it see the articles by Gingerich collected in *The Eye of Heaven: Ptolemy, Copernicus, Kepler* (New York: American Institute of Physics, 1995), 192-251; and Bruno Morando and Denis Savoie, "Etude de la théorie du Soleil de *Tables pruténiques*," *Revue d'histoire des sciences* 49 (1996): 543-67.

Reinhold's praise of Copernicus in the *Prutenic Tables* and his evident interest in *De revolutionibus* contributed for a time to a modern misconception that Reinhold himself was a Copernican and a believer in heliocentrism. The twentieth-century discoveries of his annotated copy of *De revolutionibus* and of the manuscript for his commentary on the book have shown that he never adopted a Sun-centered cosmology. Possibly he contemplated a proto-Tychonic system with the Earth at rest and the five planets circling the Sun, which would have retained the mathematical advantages of Copernicanism without the physical drawbacks. Today he is considered to be the principal founder of the Wittenberg Interpretation and the first astronomer known to have adopted the astronomical models and values in *De revolutionibus* for predictive purposes, without also adopting their heliocentric framework.[6]

Reinhold first advertised his interest in the new astronomy in the short period between the publication the *Narratio prima* in 1540 and the appearance of *De revolutionibus* in 1543. Two passages in his 1542 commentary on Peurbach refer to the work of an unnamed astronomer who is to restore astronomy by correcting the shortcomings of Ptolemy (translated in appendix 5). Reinhold cites details of the innovative astronomy unique to Copernicus, details that he could have known only through the *Narratio* or an early version of *De revolutionibus*. The astronomer, who comes from Prussia, has a double-epicyclic lunar model that adjusts the distance of the Moon. The Copernican lunar model corrected the defect in the *Almagest* that required substantial monthly variation in the distance and apparent size of the Moon. The expert

[6] The "neutrality" of Reinhold's Copernicus commentary was first pointed out in Aleksander Birkenmajer, "Le commentaire inedit d'Erasme Reinhold sur le 'De Revolutionibus' de Nicolas Copernic," in *La Science au seizieme siecle: Colloque International de Royaumont. 1-4 Juillet 1957*, ed. R. Taton and P. Costabel (Paris: Hermann, 1960), 171-77. Barker and Goldstein, "Realism and Instrumentalism," propose a set of

has also worked on the problems of the unequal length of the year and the changing obliquity of the ecliptic. Copernicus predicted both effects with the librations. If any doubt remained, it would be dispelled by the 1553 edition where an alteration has been made to the preface. The new passage reads in part: “Indeed because these hypotheses of Ptolemy do not satisfy the apparent size of the moon’s body at all rightly, [we mention] in our age the very learned Man Copernicus, who can be compared deservedly with all ancient experts of Astronomy, as we shall set forth in its place.”[7]

Reinhold saw in Copernicus the advent of the long-awaited genius capable of finishing the task of reformation started in Vienna in the fifteenth century. Yet he presents Copernicus as a conservative reformer of standard problems compatible with geocentrism, omitting to mention the new cosmology of the forthcoming book. His comments are sufficiently vague that we cannot determine whether his knowledge of Copernican astronomy when he wrote these passages came solely from the *Narratio* or from direct contact with Rheticus as well. He may even have included them as an afterthought, since the references to Copernicus appear near the end of the book and in a preface, locations that would have been printed last.

The commentary reveals that the university’s educational reform placed high demands on its students, even though Melanchthon declared that a *theorica* was necessary because “in schools the work is elementary.”[8] Clearly “elementary” is a

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characteristics shared by subscribers to the Wittenberg Interpretation that includes use of Reinhold’s works.

[7] “Verum quia hae Ptolemaei hypotheses adparenti magnitudini corporis lunae haud rite satisfaciunt, nostra aetate doctis. *Vir* Copernicus, qui cum omnibus ueterib. Astronomiae artificib. merito comparari potest, quas suo loco exponemus.” Reinhold, in Peurbach, *Theoricae novae* (Wittenberg, 1553), fol. 23r (my translation).

[8] “Scis autem in scholis opus esse elementia. Nec alius libellus magis necessarius est, quam Theoricae. . . .” *CR* 2:816; the source is Melanchthon’s preface to the *Theoricae novae* first published in 1535.

relative word, and Reinhold expected more of his students at Wittenberg than Peurbach had a century earlier. Three trends emerge from Reinhold's *scholia*, all becoming more prominent in the 1553 edition but present to some degree from the beginning.

First, the commentaries add to the mathematical content and technical level of the *Theoricae novae*. The popular medieval *theorica* presents the solar model as a simple eccentric circle, defining the lines and arcs necessary to calculate the Sun's position on the deferent. Peurbach gives a more complete and comprehensible description of the solar model as orbs, but remains at the level of narrative description. Reinhold adds simple geometrical demonstrations that help the reader understand the principles behind each model, such as how an eccentric deferent causes uniform motion to appear unequal. His additions are intended to be preliminary to reading the demonstrations in Ptolemy and other authorities. He prefaces his explanation of an epicyclic solar model with the disclaimer: "We now recount this briefly without demonstrations, which we wish to be sought from Ptolemy, Copernicus, Theon, and Regiomontanus. . . ."[9]

Reinhold included fairly advanced material in the second edition. For instance, a commentary on the lower apsis or perigee digresses into a short history of the solar model: from similar observations Hipparchus and Ptolemy found the lengths of the seasons and were able to determine the solar eccentricity and apogee. In the two centuries separating their observations the solar apogee did not change place significantly, but its motion was detected by later astronomers culminating with Copernicus. Reinhold's commentary is based on Ptolemy's derivation of the solar anomaly in the *Almagest* and

[9] "Hec breuiter nunc commemorauimus sine demonstrationibus, quas peti uloumus à Ptolemaeo, Copernico, Theone et Regiomontano. . . ." Reinhold, in Peurbach, *Theoricae novae* (Wittenberg, 1553), fol. 31v (my translation).

approaches the same technical level; in the *Almagest*, however, discussion of the solar anomaly is preceded by the observations from which Hipparchus determined the lengths of the seasons.[10] The origins of the models in the raw data of the observations constituted the final level separating the *theorica* from advanced studies at Wittenberg.

A second feature of the commentaries is the addition of many Greek words and phrases. The humanist movement of the Renaissance revived Greek as a language of learning, though it never gained the currency of Latin. Despite his involvement with the Reformation Melanchthon continued to promote the study of Greek at Wittenberg. By midcentury the mathematical lectures for advanced philosophical students included some exposure to classical astronomical texts in their original language. As professor of higher mathematics, Reinhold lectured on Ptolemy's *Almagest*; in 1549 he published an introduction to Ptolemy entitled *Mathematicae constructionis liber primus*. The textbook contained both Greek and Latin texts of the cosmological first book of the *Almagest* as well as Reinhold's commentary on mathematical aspects of the book.[11] Students at Wittenberg learned Greek as a matter of course, but they had to master the specialized vocabulary of astronomy in order to read classical sources. Definition had always been one of the functions of the *theorica* genre; Reinhold extended it to include explanations of Greek terms like *ecleiptike* and *tai phainomena*. Liberal use of Greek words and phrases become a routine part of later textbooks in the Wittenberg tradition.

A third change in the commentaries is the increase in the cosmological and

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[10] Reinhold, in Peurbach, *Theoricae novae* (Wittenberg, 1553), fol. 40v-41v; *Almagest* 3.1, pp. 131-41 (observations and derivation of year length), and 3.4, pp. 153-56 (derivation of solar anomaly for eccentric model).

[11] Ptolemy, *Ptolemaei mathematicae constructionis liber primus graece & latine editus. Additae explicationes aliquot locorum ab Erasmo Rheinholt Salveldensi* (Wittenberg: Iohannes Lufft, 1549).

physical content of the *theorica* genre. In the *Theoricae novae* itself, Peurbach made an implicit comment about the physical reality of Ptolemaic models by depicting them as cross-sections of three-dimensional orbs. Reinhold goes much further, especially in the revisions to his commentary on the Sun, where he makes several definite statements about the nature of the heavens (translated in appendix 5). The nested celestial spheres are compared to the parts of an egg and the layers of an onion. The planets are carried by orbs in a uniform motion, as Aristotle taught, rather than wandering freely through the heavens like fish in water or birds in the air. Ancient Stoics had drawn analogies between planets and terrestrial animals; sixteenth-century authors sometimes drew upon the analogy in order to uphold Aristotelianism and refute Stoic physics. It may have gained significance at Wittenberg after Luther, whose knowledge of natural philosophy was not great, compared the planets to living beings. Reinhold's insistence that planetary motion is "lawful" (*legitima*) derives from Melanchthon's vision of astronomy as a prime example of God's providential design. The section concludes with another point of Aristotelian physics; while spheres may be said to roll or rotate, only rotation is possible in the heavens.[12]

In the second edition Reinhold also introduces something entirely new to the *theorica* genre: an alternate solar model. Ptolemy opted for an eccentric for the Sun but only after demonstrating that the appearances could be saved equally well by an epicycle-on-concentric. But more elementary astronomical texts, such as the *theorica* genre, had as

[12] Reinhold, in Peurbach, *Theoricae novae* (Wittenberg, 1553), fol. 27v. For Luther's comments see Randles, *The Unmaking of the Medieval Christian Cosmos, 1500-1760: From Solid Heavens to Boundless Aether* (Aldershot: Ashgate, 1999), 34-35. The Stoic trope of birds, fish, and planets is discussed further in Barker, "Stoic Contributions to Early Modern Science," in *Atoms, Pneuma, and Tranquility: Epicurean and Stoic Themes in Early Modern Thought*, ed. Margaret J. Osler (Cambridge: Cambridge University Press, 1991), 135-54.

their primary goal the instruction of students in predicting planetary positions using astronomical tables. Before the sixteenth century, very few would go on to read the *Almagest* itself, and even fewer would understand it. Reinhold is writing for a more sophisticated audience. He expects that some of his audience will progress to the reading of Ptolemy, Copernicus, and other astronomical authorities.[13] In addition, from Melanchthon he has learned a different goal for astronomy. Besides making predictions for the practical applications of chronology and astrology, mathematicians demonstrate divine providence with their ability to calculate and explain celestial motions, and they seek to know as much as is possible and lawful about the aetherial realm as part of God's creation. Therefore it becomes important to acknowledge where the astronomer cannot determine which of two equally satisfactory models God utilized in His divine plan, even though he can be sure that one or the other describes the actual celestial orbs.[14]

For the sake of completeness, Reinhold introduces the epicycle-on-concentric beside the eccentric as a possible model for the Sun, in an explanation informed by *De revolutionibus* as well as the *Almagest*. As he explains, a solar theory requiring the motion of the apogee can be satisfied with an epicyclic model by the simple expedient of assigning the epicycle and the deferent slightly different periods. Ptolemy ascribed no motion to the solar apogee, but Copernicus devoted a chapter to this problem in *De revolutionibus*, which was the most important astronomical text to be published while

[13] For instance, "Following we shall explain the hypothesis of the Eccentric from geometrical fundamentals, so that students may prepare for the lectures on Ptolemy and Copernicus." ("Deinceps Eccentrici hypothesin ex gaeometricis fundamentis explicabimus, ut studiosum ad Ptolemaei & Copernici lectionem praeparemus.") Reinhold, in Peurbach, *Theoricae novae* (Wittenberg, 1553), fol. 32r.

[14] For a discussion of the practical difficulties of choosing astronomical models see Barker and Goldstein, "Realism and Instrumentalism"; for the connection of this problem to the view of providence espoused by Melanchthon see Barker, "Role of Religion."

Reinhold was revising his commentary. Reinhold's study of Copernicus, especially the publication of the *Prutenic Tables* and his plans to publish the commentary on *De revolutionibus*, would only have been possible in a climate where reading the book was uncontroversial. His revised commentary on the *Theoricae novae* shows that he anticipated Copernicus would be a regular part of the curriculum at Wittenberg. His successor, an outspoken geocentrist, saw fit not only to leave Reinhold's references in the posthumous edition, but also to include Copernicus in another Wittenberg textbook.

Caspar Peucer (1525-1602)

After Reinhold's death, his position was filled by Caspar Peucer, who promptly took upon himself the task of completing his predecessor's unfinished works.[15] Peucer was the third of Melanchthon's important mathematical students. He matriculated at Wittenberg in 1540 and lived with Melanchthon during his studies. In 1550 he married Melanchthon's youngest daughter, Magdalena, a sign of the close relationship between the two men, and began looking after the household for his aging but still politically active father-in-law. Peucer was appointed professor of mathematics in 1554 to fill the vacancy left by Reinhold's death; he also studied medicine, a not uncommon combination with mathematics, and became a professor in the medical faculty in 1560. Additionally, as an active lay theologian he was one of the chief advocates of Philippism in the struggle with the Gnesio-Lutherans (who claimed to represent the true teachings of Luther). He became the personal physician of Elector August of Saxony in 1570. Initially the position enabled him to assist both the university and his theological cause, but in 1574 August had Peucer and several other Philippists arrested because of their spiritualized, allegedly Calvinist interpretation of the Lord's Supper. Peucer was released after the Elector's death twelve years later, but he and other surviving Philippists had lost most of their influence at Wittenberg and in the Lutheran movement.

Peucer read widely and wrote on a number of subjects, including medicine and history; he also collected and published Melanchthon's works and letters. His mathematical texts include the *Logistice regulae arithmeticae, quam Cossam et*

[15] For biographical information on Peucer, see Robert Kolb, *Caspar Peucer's Library: Portrait of a Wittenberg Professor of the Sixteenth Century*, Sixteenth Century Bibliography 5 (St. Louis: Center for Reformation Research, 1976), 2-5; and Julius Wagenmann, "Peucer, Kaspar P." in *Allgemeine Deutsche Biographie* (Leipzig: Duncker & Humblot, 1887), 25:552-56.

Algebram vocant (1556), *De dimensione terrae* (1550); and *Elementa doctrinae de circulis coelestibus et primo motu* (1551), one of the new *sphaeras* of the sixteenth century. He also wrote a popular study of types of divination, *Commentarius de praecipuis divinationum generibus* (1553), with a chapter on astrology. Peucer's *sphaera* became the standard textbook on elementary astronomy after its publication. The discussion of the book which follows is based on the revised version.[16]

The *Elementa doctrinae* adheres to the Ptolemaic and Aristotelian worldview of older astronomical textbooks. Like Sacrobosco's *Sphaera*, it contains four parts:

> First part of the elements of the sphere, containing certain *prolegomena*.
>
> Second part of the elements of the sphere, on heaven, the stars, the orbs of the stars, and the earth.
>
> Third part of the elements of the sphere, on the celestial circles, and their use.
>
> Fourth part of the elements of the sphere, on rising and setting of the fixed Stars, on ascent and descent of the signs of the Zodiac, on the division of days and hours, on the differences of climes, and on Eclipses.[17]

The *prolegomena* explains the distinctions between astronomy and astrology. Astronomy is the science of celestial motions and is classed with arithmetic and geometry, along with the two parts of cosmography (geography and chorography, which are the large-scale and small-scale descriptions of the Earth). Astrology is the science of celestial influences and is classed with physics. Astronomy is subdivided in two parts: the

[16] Peucer, *Elementa doctrinae* (1569).

[17] "Prima pars elementorum sphaericorum, continens *prolegomena* quaedam. . . . Secunda pars elementorum sphaericorum, de coelo, stellis, stellarum orbibus, et terrae. . . . Tertii pars elementorum sphaericorum, de circulis coelestibus, et usu circulorum. . . . Quarta pars elementorum sphaericorum, de ortu atque occasu Stellarum fixarum, de ascensu descensuque signorum Zodiaci, de discrimine dierum & horarum, de climatum differentijs, de Eclipsibus." Peucer, *Elementa Doctrinae* (1569), 15, 48, 110, 188 (my translation).

first part on the first motion is contained in a *sphaera* and thus forms the subject matter of the *Elementa doctrina*; the second part on the motions of the fixed stars and the seven planets can be read about in a *theorica planetarum*. The rest of the *prolegomena* is an in-depth review of geometry, a common feature of *sphaeras* of the time. The second part, corresponding roughly to the first chapter of Sacrobosco, presents the standard picture: the world comprises two parts, the elementary and aetherial realms, with a central spherical Earth surrounded by the celestial orbs. Peucer supports his exposition with substantial physical arguments and some scriptural references. The third part, corresponding to the second chapter of Sacrobosco, explains the circles of the celestial and armillary spheres. The fourth part, corresponding roughly to the third and fourth chapters of Sacrobosco, explains risings and settings, climes, and eclipses.

Arguments for the centrality and immobility of the Earth, presented in part two of *Elementa Doctrinae*, assume a special importance in response to the recent challenge posed by Copernicus. Peucer devotes three sections to a refutation of heliocentrism with mathematical, scriptural, and physical arguments under the headings, "That the earth holds the middle place of the world, and is the center of the universe," "That the Earth remains in the middle of the world fixed and motionless," and "These are the physical reasons."[18] Virtually the entire section reproduces, word for word, the response to Copernicus made by Melanchthon in the *Initia doctrinae physicae*. Peucer has written a new introduction mentioning Copernicus by name as an imitator of Aristarchus, rearranged blocks of text, and rewritten some of the physical arguments.

Peucer moves the arguments based on astronomical observations to the front, as is

[18] "Quod terra obtineat medium mundi locum, sitque uniuersi." "Quod terra in medio mundi haereat fixa & immota." "Physicae rationes hae sunt." Peucer, *Elementa doctrinae* (1569), 100, 104, 105 (my translation).

appropriate for a mathematics textbook. These arguments, drawn from the *Almagest*, show why alternative places for the Earth would produce counterfactual phenomena:

> If indeed the earth is not in the middle of the universe, it will necessarily hold some one of these positions. Either, first, it is placed away from the axis of the world, yet in such a way that it is equally distant from the Pole in both directions, that is, so that it is in the plane of the equinoctial. . . . Or else, second, it is indeed placed on the axis of the world, but outside the plane of the equinoctial, that is, closer to one of the two poles. . . . Or else, third, it is placed neither on the axis of the world nor in the plane of the Equinoctial. . . .[19]

The argument proceeds by listing the phenomena that would be observed with the Earth at each of the three locations. In the first case, for example, the horizon for an observer at the equator would divide the sky in two unequal parts, so there would never be an equinox (which is characterized by equal lengths of day and night), while an observer at some other place on Earth might see an equinox, but not when the Sun reaches the celestial equator; the time from sunrise to noon would not equal the time from noon to sunset; and stars would appear to change sizes in the eastern and western halves of the sky, because they would approach and recede from the Earth. The structure and content of this part of the response to Copernicus follows its Ptolemaic source closely.

Further proof of the immobility of the Earth is found in a series of biblical passages that appear to speak of either the Sun's motion or the Earth's stability (Psalms 104:5, Ecclesiastes 1:5, and Psalms 19:4-5). Additionally, God's stopping the Sun is included among the miracles (an allusion to the same incident in Joshua 10:13 that Luther mentioned in the *Tischreden*). The section on arguments from scripture occupies only a

[19] Peucer, *Elementa doctrinae* (1569), 102: "Si enim terra non est in medio uniuersi, obtinebit necessario horum situum aliquem. Primus, aut est collocata extra axem mundi, ita tamen, ut aequaliter distet ab utroque Polo, hoc est, ut sit in plana superficie aequinoctialis. . . . Secundus, aut est quidem sita in axe mundi, sed extra superficiem planam Aequinoctialis, hoc est, alterutri polorum propior est. . . . Tertius, aut neque in axe mundi sita est neque in plano Aequinoctialis. . . ." (my translation). Compare *Almagest* 1.5, p. 41.

small part of the refutation of heliocentrism. In the context of the arts curriculum, theology receives due respect but does not supercede philosophical concerns.

The third and final section refutes the notion of a moving Earth with Aristotelian tenets about place and motion. For example, as a simple body, the Earth can have only one simple motion. Since it naturally moves rectilinearly towards the center, it cannot also possess a circular motion. The physical arguments are based on standard arguments in Aristotle's *De caelo* and Ptolemy's *Almagest*. Accepting them requires prior acceptance of Aristotelian physical doctrine, which was the only fully developed system of physics available for much of the sixteenth century.

Peucer balances his firm rejection of heliocentrism with a positive opinion of Copernicus' contribution to astronomy. In the very same section in which he criticizes a moving Earth, Peucer says that Copernicus "wrote the most important work about the doctrine of the Stars after Ptolemy."[20] Elsewhere he adopts Copernican values for the distances of the Sun and Moon alongside Ptolemaic values for planetary distances. The greatest and least distances for the stars and planets--or the distances to the inner and outer surfaces of their orbs--were a standard part of the Greek astronomical tradition, together with their diameters and even their volumes. Peucer distributed his discussion of sizes and distances in two sections, "What the situation of the celestial orbs is, and how great the distance from the earth," and "On the Planets."[21] The values are interspersed with planetary lore common to the Roman and early medieval handbook traditions such as Martianus Capella and Macrobius. The paragraphs on Saturn give an impression of the

[20] ". . . qui post Ptolemaeum de doctrina Astrorum scripserunt summus," Peucer, *Elementa doctrinae* (1569), 100 (my translation).

[21] "Quis sit coelestium orbium situs, & quanta a terra distantia"; "De Planetis," Peucer, *Elementa doctrinae*

character of Peucer's descriptions of the planets:

> The higher apsis [apogee] of Saturn's orb, which today is in the 29th part of Sagittarius, twenty thousand seventy two and a quarter Semidiameters from earth, about 20,072 and 15 minutes. Indeed, the lower apsis [perigee] is distant fourteen thousand three hundred seventy eight and a third, 14,378 and 20 minutes.[22]

> Saturn the highest of the planets, and slowest, cold and dry, pallid, leaden in color, completes its course in 30 years, and is ninety times and one eighth part larger than the earth. For the proportion of its diameter to the diameter of the earth is four times one and a half times, which is 9 to 2. In Greek it is called *kronos* from "time" because of slower motion. It is also called *phainon*.[23]

Peucer presents values for celestial sizes and distances haphazardly; sometimes he gives one set of values, sometimes two, and he may or may not name authorities (Peucer's distances are summarized in appendix 6). In many instances his sizes and distances do not agree with any of the four popular sets of values calculated by Ptolemy, al-Farghānī, al-Battānī, and Campanus of Novara.[24] According to Peucer, Ptolemy found the minimum and maximum distances of the Sun to be 1,120 e.r. and 1,210 e.r. But Ptolemy gave 1,210 e.r. as the mean distance of the Sun (between the limits of 1,160 e.r. and 1,260 e.r.). In fact, 1,120 e.r. is the minimum according to al-Farghānī, who is not named anywhere in the sections on measurements. The only astronomer whom Peucer consistently cites correctly is Copernicus, whose figures are sometimes attributed only to

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(1569), 71, 82 (my translation).

[22] "Orbis Saturni summa Absis, quae hodie est in 29 parte Sagittarij, a terra Semidiametris uicies millibus septuaginta duabus cum quadrante, fere 20072 se: & 15 scrup. Ima uero absis, decies quater millibus trecentis septuaginta octo cum triente, 14378. se. & 20. scrup. abest." Peucer, *Elementa doctrinae* (1569), 74-75 (my translation).

[23] "Saturnus supremus Planetarum, & tardissimus, frigidus & siccus, pallidus, colore plumbeo, 30. annis cursam conficit, terra maior nonagies semel cum octaua parte. Proportio enim diametri eius ad diametrum terra quadrupla est sesquialtera, quae 9. ad 2. graece *kronos* a tempore ob tardiorem motum dicitur. Vocatur & *phainon*." Peucer, *Elementa doctrinae* (1569), 82 (my translation).

[24] For a summary of Ptolemy's numbers, see appendix two; for those of al-Farghānī and al-Battānī, see Van Helden, *Measuring the Universe*, 30 and 32; for those of Campanus of Novara, see his *Theorica planetarum*, 186-193, 238-243, 322-345.

“more recent people” (*recentiores*), where there is only one mistake (the current eccentricity of the Sun is given as 1;56 but should be 1;51). The errors may be due to carelessness on the part of the printer, though the fact that many numbers are written out should should have served as a safeguard. Furthermore, a few of the values are part of the astronomical tradition, though incorrectly ascribed, which precludes purely random sources of error.

Despite the errors, readers of the *Elementa doctrinae* would have gained an approximate idea of the sizes and distances of celestial bodies. They would have learned, further, that the planets had decreased in distance from the Earth since antiquity. For Mars, the Sun, and Venus, Peucer attributes the reduced distances to a change in the eccentricity of the deferent. For the case of the Sun, the change proceeds from a feature of Copernicus’ theory of terrestrial motion, the second or twofold inequality. The decrease in eccentricity is caused by the motion of the center of the Earth’s deferent on a small circle in a 3,434 year cycle. Peucer’s use of the tradition of celestial measurements shows two ways Copernicus could be accommodated to earlier authorities. In some instances, his figures are said to be more exact, presumably because of more accurate observations or better calculations, but the changing eccentricities and distances are attributed to the astronomical models themselves, which only Copernicus has been able to describe in full.

Michael Maestlin (1550-1631)

The last figure to be discussed in this chapter is Michael Maestlin.[25] As a member of a later generation of Lutherans, Maestlin represents Melanchthon's success in establishing a reformed curriculum with a mathematical component at Lutheran universities beyond Wittenberg. He studied both the arts and theology at the University of Tübingen, where Melanchthon had been trained as a Greek humanist decades earlier. He substituted briefly for the mathematics professor Philipp Apian (1531-1589), who went on leave in 1575. Late the following year he was appointed a pastor in Backnang. The backlash against Philippism, so deleterious to Peucer, proved beneficial to Maestlin's career. He was appointed professor of mathematics at Heidelberg in 1580, after the elimination of suspected Calvinists left a vacancy, and four years later he returned to Tübingen to replace his former teacher Apian, who had refused to sign the Formula of Concord. He taught mathematics there for the remainder of his long life. Maestlin is best remembered today in his capacity as a teacher due to his influence on Johannes Kepler (1571-1630), who learned from him not only the Copernican doctrine, but also the understanding that in astronomy lay a powerful tool for discovering divine providence.[26]

Far from being a monolithic worldview, Aristotelianism manifested in diverse ways over the roughly two millennia of its existence. Even though he differed from Aristotelian natural philosophy on many points, Maestlin remained in agreement with the

[25] For biographical information on Maestlin, see *DSB* 9:167-70; and for an overview of his work in astronomy see Richard A. Jarrell, "Mästlin's Place in Astronomy," *Physis* 17 (1975): 1-20.

[26] The most extended recent study of relations between astronomy and theology at Tübingen, where Maestlin spent most of his life, is Charlotte Methuen, *Kepler's Tübingen: Stimulus to a Theological Mathematics* (Aldershot: Ashgate, 1999). See also Barker and Goldstein, "Theological foundations of Kepler's astronomy," in *Science in Theistic Contexts: Cognitive Dimensions*, ed. John Hedley Brooke, Margaret J. Osler, and Jitse van der Meer, *Osiris*, 2nd ser., 16 (2001): 88-113; and for a critique of Methuen see Barker, "Astronomy, Providence, and Lutheran Contribution."

general Aristotelian worldview. He publicly endorsed the radical cosmology of heliocentrism that upset cherished tenets of Aristotelian physics by introducing a moving and noncentral Earth. Simultaneously, he adhered to Aristotelian methodology and accepted some aspects of established physics. He retained Aristotle's doctrine of causes and insisted that complex celestial motions were created by combinations of rotating orbs, just as Ptolemy had described centuries earlier. The attempt to understand Maestlin's natural philosophy is complicated by the fact that he strictly followed the traditional model of teaching astronomy in his published textbook, even to the point of teaching geocentrism rather than heliocentrism. We know that he taught the Copernican cosmology to select students mainly from Kepler's reports, though an exception appears below. Any retrospective account almost inevitably makes Maestlin appear an awkward transitional figure in the history of Copernicanism, but as I hope to show, his ideas were continuous with those of his Lutheran predecessors.[27]

In 1570 Maestlin obtained a copy of *De revolutionibus*, and the next year he published a new edition of Reinhold's *Prutenic Tables*. Since the two books were core texts of the Wittenberg Interpretation, they cannot be taken as indications of Maestlin's incipient Copernicanism, but they show that he knew of and perhaps was intrigued by heliocentrism. In 1572 he had the opportunity to observe a new star in the heavens. By holding up a piece of string he was able to align the nova with fixed stars. He then checked their positions in a star catalogue and calculated the position of the nova. He

[27] Methuen, "Maestlin's Teaching of Copernicus: The Evidence of His University Textbook and Disputations," *Isis* 87 (1996): 230-47; Methuen, "The Teaching of Aristotle in Late Sixteenth-Century Tübingen," in *Philosophy in the Sixteenth and Seventeenth Centuries: Conversations with Aristotle*, ed. Constance Blackwell and Sachiko Kusukawa (Aldershot: Ashgate, 1999), 198-204. In the latter article, Methuen argues that Maestlin's attitude toward Aristotelianism is the product of the humanist preference for original texts; in the case of mathematics, the "text" is nature.

found that the new star had no measurable parallax, meaning that it had arisen well beyond the sphere of the Moon even though change in the aetherial realm was theoretically impossible. In a short treatise on the nova, he placed it amongst the fixed stars. Significantly, he stated that the distance of the stars was much greater according to the work of Copernicus. Whereas Copernicus' recalculated distances for the Sun and Moon could be used in any cosmology, placing the fixed stars at an enormous distance becomes necessary only when accepting the annual motion of the Earth.[28]

The earliest indisputable evidence for Maestlin's support of heliocentrism comes from his study of the comet of 1577, which was observed by many astronomers across Europe. Employing the same method he had applied to the nova, Maestlin found that the comet similarly contradicted the Aristotelian doctrine that restricted transitory phenomena to the elementary sphere. He found, furthermore, that in a geocentric system the path of the comet would pass through planetary spheres. Tycho Brahe, who observed the comet at Hven, reached similar conclusions; his solution was to replace Aristotelian celestial spheres with liquid aether, modeled on Stoic physics, which also accommodated a geo-heliocentric or Tychonic cosmology. Maestlin remained committed to non-intersecting spheres and was already leaning towards Copernicanism. In *Observatio & demonstratio cometae aetherei* (1578), he determined that the comet would cross no celestial barriers in a heliocentric system. First he proposed that the motion of the comet was consistent with the orb of Venus according to Copernican astronomy. With further calculations he showed that the comet was located on an orb between Venus and the

[28] Maestlin, *Demonstratio astronomica loci stellae novae, tum respectu centri mundi, tum respectu signiferi & aequinoctialis* (1573), published in Tycho Brahe, *Tychonis Brahe Opera Omnia*, ed. J. L. E. Dreyer (Copenhagen: Libraria Gyldendaliana, 1913-29), 3:58-62.

Earth. To be precise, the radius of its orb is 8,420 units, where the radius of the Great Orb of the Earth is 10,000 and the radius of Venus' orb is the Copernican value of 7,193. Kepler later cited Maestlin's work on the comet as proof of heliocentrism.[29]

Although Maestlin reportedly taught Copernican astronomy to some students and perhaps introduced it routinely in his lectures on astronomy, the coverage of subjects in his textbook *Epitome astronomiae* conservatively imitates established patterns of teaching. Following a *prolegomena* of "geometrical vocabulary and principles necessary to the understanding of astronomy," the *Epitome* contains four books, each divided into several parts.[30] The first book introduces the fundamental principles of Aristotelian cosmology, which are drawn from physics as much as astronomy per se. The second book explains the use of the armillary sphere (*Sphaerae materialis*) and the *Theoriarum partes*, or parts of the *theorias*. Maestlin clearly distinguishes *theoria* from *theorica*; the latter refers to a teaching text on planetary motions, while the former applies to the "likenesses" of the orbs "by which the rule of motion of either the sphere of fixed stars or of any of the planets is to be demonstrated."[31] The third and fourth books are Maestlin's *sphaera* and *theorica*, on the first and second motions of the heavens.

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[29] Maestlin, *Observatio & demonstratio cometae aetherei, qui anno 1577. et 1578. constitutis in sphaera veneris apparuit*... (Tübingen: Georgius Gruppenbachius, 1578). For background and analysis see C. Doris Hellman, *The Comet of 1577: Its Place in the History of Astronomy* (New York: AMS Press, 1971), esp. 137-59; Westman, "The Comet and the Cosmos: Kepler, Mästlin and the Copernican Hypothesis," in *The Reception of Copernicus' Heliocentric Theory*, ed. Jerzy Dobrzycki (Dordrecht: D. Reidel, 1972): 7-30 (where the influence on Kepler is mentioned); Westman, "Michael Maestlin's Adoption of the Copernican Theory," in *Colloquia Copernicana IV*, Studia Copernicana 14 (Wrocław: Ossolineum, 1975), 53-64; and Barker and Goldstein, "Theological foundations of Kepler's astronomy."

[30] "Prolegomena in epitomen astronomiae, quae continent vocabula & principia Geometrica, ad congnitionem Astronomiae necessaria." Maestlin, *Epitome astronomiae* (1610), 1 (my translation). Maestlin outlines the book on page 20.

[31] "Quid sunt Theoriae Planetarum vel secundorum mobilium? Sunt effigies sphaerae stellarum fixarum, vel alicuius ex septem erraticis, ex certis quibusdam Orbibus se mutuo ambientibus, artificiosè extructae, quibus vel sphaerae stellarum fixarum, vel alicuius Planetae motus ratio demonstratur." Maestlin, *Epitome*

Maestlin's style of presentation is systematic and thorough. It also exhibits the most self-conscious application of Aristotelian concepts in any of the astronomical books discussed so far. Maestlin respects and even clarifies the disciplinary division between physics and astronomy: only the physicist may discuss efficient and final causes, while the astronomer is restricted to formal and material causes (the shape and substance of the heavens). To proceed in astronomy, one must accept a set of propositions about the universe; physics, on the other hand, is capable of providing demonstrations for those propositions. This conservatism is all the more surprising in light of his favorable attitude towards heliocentrism, since the work of Copernicus challenged the subordination of mathematics to physics by privileging the mathematical demonstration of cosmology.[32]

In early editions of the *Epitome*, Maestlin included solar and lunar minimums and maximums. When combined with the relative sizes of each orb in the remaining planetary models, such as the eccentricity and the radius of the epicycle in relation to the radius of the eccentric, distances for the two luminaries could be used to find the distances of the five planets, following a procedure similar to Ptolemy's in the *Planetary Hypotheses*. Maestlin supplied the proportions for each model but did include absolute distances. In later editions he expanded Book 1 with an appendix on measuring the Earth. Editions from 1598 and later include an expanded appendix with planetary distances given in terms of the Earth's radius (appendix 7). A chart supplies Al-Farghānī's minimum and maximum distances for each planet; unlike Peucer, Maestlin cites appropriate values. Furthermore, he provides a superior demonstration of the nesting principle because the

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astronomiae (1610), 24 (my translation).

[32] Maestlin, *Epitome astronomiae* (1610), 30-31, 41. On the issue of method see Westman, "The Astronomer's Role in the Sixteenth Century: A Preliminary Study," *History of Science* 18 (1980): 105-147.

spheres are contiguous. Al-Farghānī took the maximum distance of each planet as the minimum of the next one, whereas Ptolemy left a gap between Venus and the Sun (and possibly also between Saturn and the fixed stars), and Peucer's eclectic values rarely match up.

The discussion of celestial distances has a surprising didactic aim. After determining the distance to the inner surface of the sphere of fixed stars, which in the Ptolemaic system is considered to be approximately equal to the greatest distance of Saturn, Maestlin finds the sphere's circumference in miles. Since the sphere completes one rotation every twenty-four hours, it is also the distance a star on the celestial equator must travel in a day. It then becomes possible to calculate how far the star must travel in an hour (1/24 of the circumference) or even the duration of a single pulse (1/4,000 of the distance traversed in an hour). Given al-Farghānī's value of 20,110 e.r. as the distance to the stars, in a single pulse the star must travel a staggering 1,132 miles. It is absurd, Maestlin argues, to suppose that something as noble as the celestial realm is perpetually moving so swiftly. He also shows that even Tycho's much smaller estimate for the size of the universe--a mere 13,000 to 14,000 e.r. to the fixed stars--requires that the same star travel at least 732 miles in one pulse. The only way out of this difficulty is to accept the Copernican alternative: the Earth rotates daily at a much smaller speed, while the enormous heavens stand still. Thus, one avoids the "incomprehensible and incredible swiftness" of the daily motion while gaining a system that "corresponds better with Reason, with Nature, and with Observations."[33] Maestlin published a similar version of

[33] "Inter caeteras rationes, quae Copernico de alijs hypothesibus, aliaqúe Sphaerarum Mundi dispositione, quae cum Ratione, cum Natura & Obseruationibus melius corresponderent, cogitandi occasionem praebuerunt, haec incomprehensibilis & incredibilis in celeritate rapiditas, haud dubiè non postrema, si modò non prima, fuit." Maestlin, *Epitome astronomiae* (1610), 94-95 (my translation).

the argument with a new edition of Rheticus' *Narratio* to be appended to Kepler's first book, the *Mysterium Cosmographicum*, in 1596. The same process that showed up the absurdity of celestial rotation would also have made an excellent teaching exercise, since it gave practice in calculating radii and circumferences, and in converting units of measurement.[34]

Maestlin's appendix supplies only the greatest and least possible distances for each celestial body; its chief surprises are the addition of two alternative solar measurements. Ptolemy's greatest distance for the Sun is given as 1,210 e.r.; this was actually his mean distance in the *Almagest*, but as we saw, Peucer made the same attribution. Copernicus' least and greatest distances for the Sun are given as 1,094 e.r. and 1,190 e.r., yet in *De revolutionibus*, Copernicus finds the distances to be 1,105 e.r. and 1,142 e.r. The reason for this discrepancy becomes clear much later in the *Epitome*. The *theorica* includes both Ptolemaic and Copernican planetary models, with the latter adjusted to a geocentric framework. The chapter on the Moon, for instance, mentions the Copernican double epicyclic model along with the Ptolemaic epicycle on eccentric. In the case of the Sun, the two models are the simple eccentric and the double eccentric.[35] A section on the sizes of the solar orbs shows that the source of Maestlin's apparent divergence from Copernicus is the changing solar eccentricity. At minimum eccentricity, the Sun follows a more nearly concentric circle, but it reaches more extreme distances at maximum eccentricity.

Copernicus gave only the distances for his time, when the eccentricity was least.

[34] Compare Maestlin, in Kepler, *Mysterium cosmographicum* (1596), 88. I have traced Maestlin's development of the "argument from swiftness" more fully in "Maestlin and the *Narratio*."

[35] Maestlin, *Epitome* (1610), 334 (solar model), 346 (lunar model).

In the appendix on measurements, Maestlin gives only the extremes, which define the limits of the solar sphere, but in the more advanced *theorica*, which presents planetary models in detail, he gives both sets of solar distances and shows how they derive from the parameters of the model. A significant difference between Copernican and Ptolemaic astronomy is that in Copernican models, the planets may not always reach the surfaces of their spheres, while in Ptolemaic models, the extreme distances of the planets and the boundaries of their spheres are assumed to be equal. Maestlin illustrated this principle in a treatise on measurements according to Reinhold's *Prutenic Tables* that he wrote for Kepler; the treatise was later included in the *Mysterium*.[36] Peucer anticipated this development in a limited way when he attributed differences in planetary distances to an actual change in eccentricity, rather than a simple disagreement over parameters between ancient and medieval authorities.

Maestlin's attitude toward the material he taught is difficult to discern. Did he teach geocentric astronomy and outdated planetary models because he was pressured to do so by the university, or because he felt the traditional view was the easiest to understand? In later editions, the appendix on planetary distances would have been read by novice students, so he must have discussed alternate cosmologies in class and advocated a position that was still in the minority. At minimum, he believed that combinations of orbs existed in the heavens: "it is manifest that those circles and orbs (although they are called Mathematical fictions by not a few) are not like the fictions of the Poets about Centaurs, which correspond to no Natural Thing outside the intellect; but

[36] For a translation of the treatise see Anthony Grafton, "Michael Maestlin's Account of Copernican Planetary Theory," *Proceedings of the American Philosophical Society* 117 (1973): 523-50.

they are images of either lawful or physical things existing in reality."[37] An appendix to the first part of book four confirms that Maestlin is fully aware of the problem of the interchangeability of eccentric and epicyclic models, yet distinguishes it from the complete dismissal of such orbs by Stoics, who imagine the stars to move like birds or fish, and Averroists, who replace complex orb systems with simple circular motions.[38] In this respect, he agrees with the legacy of the Wittenberg Interpretation. Even though alternate models may save the appearances, one of the models must be a true image of the heavens.

[37] "Hinc igitur manifestum est, Circulos & orbes illos (quanquam à nonnullis figmenta Mathematica appellentur) non esse tanquam Poëtarum de Centauris figmenta, quibus exta intellectum nihil in Rerum Natura correspondet: sed esse imagines rerum vel *thesei* vel *physei* reuera existentium." Maestlin, *Epitome astronomiae* (1610), 29 (my translation).

[38] Maestlin, *Epitome astronomiae* (1610), 433-35.

Conclusions

Taken together, Rheticus, Reinhold, Peucer, and Maestlin confirm the success of the program of astronomical reform that began with Regiomontanus in the later fifteenth century. The rediscovery of Ptolemy during the general revival of knowledge in the twelfth and thirteenth centuries is sometimes perceived as an end-point, and the creation of a *theorica planetarum* becomes the emblem of the institutionalization of predictive astronomy with its associated deferents, epicycles, and equants.[39] But it was equally the beginning of a struggle towards a more sophisticated understanding of Ptolemaic astronomy, leading to the adoption of its basic methodology as well as the critique of its shortcomings, great and small. I have given special attention to three areas of reform: the motion of the Sun, the order of the planets, and the determination of cosmic distances. Western astronomers of the late Middle Ages were aware of the shortcomings of Ptolemy's solar model and precession theory; Copernicus was hailed as the new authority on trepidation and other very slow celestial motions. The order of the planets was set only by convention in 1500, but for early followers of Copernicus, a mathematical solution could at last be found. The calculation of distances overlapped with the problem of planetary ordering but also with the unlikely lunar distances necessitated by Ptolemy's model for the Moon; Copernicus minimized changes in lunar distance.

The increase in the size of standard astronomical textbooks can be taken as an indicator of growing mathematical competency and of a rising standard of what an elementary student should know. At Wittenberg, the trend towards larger textbooks appears with the publication of Reinhold's commentary on Peurbach in 1542. As more

[39] McCluskey, *Astronomies and Cultures in Early Medieval Europe*.

and more information was added to the *sphaeras* and *theoricas*, their readers encountered problems that had been the preserve of a handful of specialists in the Middle Ages, such as the interchangeability of eccentrics and epicycles. The geographical sections of *sphaeras* likewise increased in both size and complexity, in parallel with the voyages of exploration and the rapid increase in geographical knowledge at this time. Less than a century earlier, the Greek manuscript of the *Almagest* brought to western Europe by Cardinal Bessarion was a great rarity; Regiomontanus and Peurbach had been virtually the only astronomers able to understand its contents. Melanchthon succeeded in raising standards until students routinely studied technical material and read from the *Almagest* in Greek.

Copernicus enters into this story as an unexpected yet not unwelcome reformer. Scarcely any mathematicians from the first generations after the publication of *De revolutionibus* became Copernicans themselves. Among our small group of astronomers, Reinhold wrote nothing that has survived about the matter of heliocentrism; he continued to repeat, and perhaps accept, the standard arguments for the Earth's centrality and immobility in his commentary on the *Almagest*. Peucer took a stronger stand, arguing with Melanchthon that three separate sources of knowledge--mathematics, physics and Scripture--all disproved the Copernican hypothesis. The other two became heliocentrists but chose for part of their life not to publicize their atypical cosmology; Maestlin gradually published stronger Copernican statements, while Rheticus allowed his early apparent enthusiasm to dwindle.

The question of cosmology had always been a set topic of the astronomical genre. Both Ptolemy in the *Almagest* and Sacrobosco in his *Sphaera* offer evidence that the

Earth was fixed and motionless in the middle of the universe, as the center of the circles in which the celestial orbs eternally carried the planets and the stars. Their arguments have the character of established knowledge, as though they were reviewing propositions to which they expect general assent. After 1543, cosmological discussions took on a new urgency. The possibility of meeting someone who disagreed about the foundations of astronomy, or at least of reading their work, suddenly became very real. Peucer explains Copernican doctrine so that he can refute it. By 1610, Maestlin anticipates that his students are somewhat familiar with both Copernicus and Tycho, so that he can make casual references to both authorities in his appendix on sizes and distances.

As "another Ptolemy," Copernicus became a prominent element in sixteenth-century astronomy. In introductory books like the *sphaeras* of Peucer and Maestlin, we should not expect to find the use of deferents and epicycles in model-building. For a *sphaera*, Copernicus' main role is as the source of recent, improved celestial measurements and as the latest authority on the obliquity of the ecliptic. In their discussions of planetary distances, Peucer and Maestlin include only the distances of Sun and Moon from *De revolutionibus*. The two luminaries were the only objects whose distances could be measured directly, so they served as the basis for assigning values to the five planets and the stars. Moreover, they were the only celestial bodies to retain the same relative distances from the Earth regardless of which system was adopted. The nesting principle would have undermined an attempt to convert the other planetary distances of *De revolutionibus* to a geocentric framework.

In the next two chapters I turn to astronomy in Tudor England, which was different from Lutheran astronomy but dependent on it. The authors we have examined so far were elite practitioners writing for an audience committed to education. English textbook authors sought to reach a wider group and emphasized writing in the vernacular. The English reform of astronomical education proceeded with a substantial handicap, since it could not look to extant *sphaeras* and *theoricas* as a starting-point. In creating their textbooks, English writers looked to Lutheran prototypes and their remarkable discovery of Copernicus as one way of gaining access to the best astronomy of the time.

CHAPTER SIX

THE EXACT SCIENCES IN EARLY TUDOR ENGLAND

The study of philosophy and the liberal arts thrived in medieval England. The University of Oxford supported a major arts faculty, of second rank only in comparison to the great University of Paris itself. Prominent scientific figures of the Middle Ages associated with England include Roger Bacon, promoter of mathematics and student of optics; Duns Scotus and William of Ockham, central figures in the debate between realism and nominalism; and the Merton scholars of Oxford. Such a high level of prominence in scientific affairs did not extend to the early modern period. In 1542, Robert Recorde began his arithmetic textbook with the complaint: “Sore oftentymes haue I lamented with my self the infortunate condition of England; seyng so many great clerkes to aryse in sundry other partes of the worlde, and so few to apere in this our nation. . . .”[1] Undoubtedly Recorde and his fellow textbook authors exaggerated the backwards state of their country to emphasize their own contributions; nevertheless, they participated in a general belief that England was not at the forefront of mathematical studies. Recorde’s comment contrasts dramatically with an oration written by Melanchthon for Caspar Cruciger, which calls Wittenberg a “society of the best and most

[1] Recorde, *The Ground of Artes Teachyng the worke and practise of Arithmetike* (London: Reynold Wolff, 1542), fol. a2r.

learned men," and boasts of the clarity of its philosophical and mathematical teachings.[2]

The cause or causes of England's decline in scientific activity and influence remain unclear. William Courtenay has suggested the initial outbreak of plague in 1349 and 1350 as an indirect factor. After teachers at all levels succumbed to the plague, grammar-school education declined and students entering Oxford devoted more time to remedial studies. The decline in activity was relative, not absolute. My argument is for a relative decrease in the importance and originality of English authors, not for a complete cessation of all mathematical study, at the universities or privately.[3]

For England, the sixteenth century became a time of educational reform parallel to the one taking place in Lutheran universities; in both cases, the reform effort included but was not limited to improving the level of education in the mathematical arts. The differences are equally great. In Lutheran Germany, improvements were initiated by a single figure, Melanchthon, who was able to modify the existing institutional structure of the University of Wittenberg in accordance with his personal vision. It became a comparatively simple matter for other universities to incorporate similar requirements into their statutes or to hire graduates of Wittenberg to improve their own teaching. The educational movement in England was decentralized and poorly planned: individuals called out for new mathematical textbooks and new curricula emphasizing the study of nature, or spontaneously wrote the texts and taught the material themselves as they perceived the need or the opportunity. This educational movement largely passed over

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[2] Melanchthon, *Orations*, transl. Salazar, 3, 7.

[3] William J. Courtenay, "The Effect of the Black Death on English Higher Education," *Speculum* 55 (1980): 696-714. Mordecai Feingold, *The Mathematicians' Apprenticeship: Science, Universities, and Society in England, 1560-1640* (Cambridge: Cambridge University Press, 1984) has demonstrated the continued presence of mathematical studies at English universities.

such mathematical education as was provided by English universities in favor of private study and the foundation of academies oriented towards practicality.[4] The target audiences were not theologians but tradesmen, gentlemen, and the nobility, who often did not read Latin, the language of learning. Producing English-language textbooks, through translation or original composition, became a perennial issue among educational reformers, who called for contributions by skilled translators in cases where they themselves did not translate.[5]

The aspiration to join the ranks of the great European powers drove the movement to build up the study of mathematics. Other seagoing nations, above all Spain, had prospered from the discovery and exploitation of strange lands. At the same time, England was in danger of coming under the control of a stronger nation. The risk became greatest after 1558, when Elizabeth inherited the throne. Up to that point, England had vacillated between Protestantism and Catholicism; most recently, with Mary on the throne and married to Philip of Spain, it had been a Catholic state enjoying cordial relations with a dominant European power. But Elizabeth was a living symbol of the Reformation in England thanks to the circumstances behind her parents' marriage. Under her, the English found themselves in the uncomfortable position of being the only potential Protestant power to balance the Catholic superpowers of France and Spain.

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[4] While Feingold, *Mathematicians' Apprenticeship*, has discredited the notion that mathematics was entirely absent from English universities and that all serious study took place privately, the general level of mathematics at universities remained modest in comparison with many areas in the sixteenth century. Christopher Hill, *Intellectual Origins of the English Revolution Revisited* (Oxford: Clarendon Press, 1997), provides an overview of scientific activity outside the universities.

[5] Much of the evidence for the improvement of education is collected in Louis B. Wright, *Middle-Class Culture in Elizabethan England* (Chapel Hill: University of North Carolina Press, 1935); on language issues see especially chapter 10, "The Pathway to Foreign Learning and Languages," 339-72. The availability of astronomical texts in English is a central theme of the classic study by Francis R. Johnson, *Astronomical Thought in Renaissance England: A Study of the English Scientific Writings from 1500 to 1645* (Baltimore: Johns Hopkins Press, 1937; reprint, New York: Octagon Books, 1968).

Similar forces were not in operation in German-speaking territories because they lacked unity; rather than being a modern nation state, they were ruled by princes with a strong sense of independence.[6] For security as well as prosperity, England would have to become competitive. The technology of the day demanded a moderate level of scientific knowledge. Experts in ballistics, architecture, surveying, and instrument-making first had to learn mathematics, and the gentlemen who would supervise them likewise required a basic understanding of the arts.

In this chapter I discuss the initial stages of the new English educational program primarily in regard to astronomy. Besides being a field of study with a long and dignified pedigree in its own right, astronomy gained new prestige in the Renaissance as it applied to oceanic navigation. I begin with an overview of traditional methods of pilotage in the Mediterranean and southern Europe, contrasting them with the navigational techniques developed by the Portuguese that made the Age of Discovery possible. In the next section, I turn to the first signs of English concern with mathematical studies, which predate the period of greatest interest in its utility for exploration. The voices raised most strongly in favor of mathematical education in the first half of the century tend to be members of the early Tudor humanist movement. In the third section I survey the astronomical literature available in English through mid-century, including the first published English-language *sphaera*. This is followed by a close look at an influential

[6] Christopher Haigh, *English Reformations: Religion, Politics, and Society under the Tudors* (Oxford: Clarendon Press, 1993) argues the contingent nature of the Reformation in England. Melanchthon's life was profoundly affected by the turbulence caused by lack of German unification. The many talks he attended were attempts to work out political as well as religious differences. In 1546 and 1547 the University of Wittenberg was closed down during the Schmalkaldic War; the territory in which Wittenberg was located was invaded and ultimately passed to Maurice of Saxony, who was persuaded by Melanchthon to reopen the university. For the nobility to engage in warfare on such a magnitude, without interference from the Crown, would have been unthinkable in Tudor England.

early *sphaera* written by the popular textbook author Robert Recorde. I conclude with the first English experiences with astronomical navigation in the north Atlantic during the period from the 1490s to the 1550s. England depended most heavily on foreign navigators during this time. A partially successful trade expedition in 1553 established the basis for a homegrown industry of sailing and exploration that would ultimately place England among the chief sea powers.

The Development of Astronomical Navigation

As a historiographic tool, the Age of Discovery has undergone a shift not dissimilar to that which has affected the Scientific Revolution. Historians once approached the European expeditions of the fifteenth and sixteenth centuries as a time of sudden, unprecedented growth to be contrasted with the parochial isolation and stagnation of the Middle Ages. Famous voyages like Marco Polo's trip to China and the short-lived Scandinavian colonies in North America were treated as heroic aberrations. Archaeological discoveries and a fresh look at written sources once ignored have contributed to a re-assessment of medieval knowledge of and contact with the rest of the world. Seen in this context, the apparent burst in exploration that accompanied the Renaissance becomes a new phase of increased activity which built on a limited yet very real tradition of travel outside western Europe.[7]

An accident of geography helped to create two divergent attitudes toward marine exploration along the Atlantic seaboard by the fifteenth century. A series of islands bordering the North Atlantic--the Orkneys, the Shetlands, the Faeroes, and the sizeable islands of Iceland and Greenland--fostered the belief that the ocean was dotted with land. A strategy of island-hopping combined with obscure but probably empirical methods of navigation enabled northern European ships to reach far across the Atlantic.[8] No such islands awaited discovery near the more southerly regions. Medieval Europeans did not

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[7] For an overview of the extent of European travel and geographical knowledge between the eleventh and the fifteenth centuries see J. R. S. Phillips, *The Medieval Expansion of Europe*, 2nd ed. (Oxford: Clarendon Press, 1998), which includes excellent bibliographical essays; and the classic work by John Kirtland Wright, *The Geographical Lore of the Time of the Crusades: A Study in the History of Medieval Science and Tradition in Western Europe* (New York: American Geographical Society, 1925).

[8] G. J. Marcus, *The Conquest of the North Atlantic* (Woodbridge: Boydell Press, 1980). I return to this subject in the last section of this chapter, in the context of early English voyages.

sail down the west coast of Africa, perhaps because it was under Muslim control, so they did not discover the island chains lying off the African coast until late in the Middle Ages. Southern Europeans did not attempt ocean crossings in the Renaissance and the period immediately preceding; instead they crossed the Mediterranean or kept close to the Atlantic coast, and developed methods of navigation suited to traversing well-known waters near land.[9] The southern attitude was perhaps enhanced by the greater influence there of classical culture, which held that the Atlantic was an unnavigable ocean. England was ideally situated to reach the island chains of the North Atlantic, yet sufficiently far south to be influenced by the countries of the Mediterranean; it could readily participate in either tradition when societal factors were right.

The geographical situation of southern Europe necessitated a change in navigational practices if ships were to cross the deep ocean and return reliably to trading ports. Mariners eventually solved the problem of finding their way through the seemingly featureless waters by applying mathematically sophisticated astronomy to the problem of locating themselves geographically.[10] In addition to describing the development of nautical astronomy from older methods of pilotage, I offer some reasons why the Portuguese, rather than, say, the Spanish or the Italians, were at the forefront of this

[9] The "discovery" of the Atlantic between the thirteenth and fifteenth centuries is argued in Randles, "The Atlantic in European Cartography and Culture from the Middle Ages to the Renaissance," in *GCNS*. Randles' primary subject is the classically-influenced learned tradition emanating from countries bordering the Mediterranean. He shows no awareness of the adventurous northern tradition and creates the impression of unanimous European ignorance of the Atlantic.

[10] The standard accounts of Renaissance navigation in English are E. G. R. Taylor, *The Haven-Finding Art: A History of Navigation from Odysseus to Captain Cook* (New York: Abelard-Schuman, 1957); David W. Waters, *The Art of Navigation in England in Elizabethan and Early Stuart Times* (London: Hollis & Carter, 1958); and Waters, "Science and the Techniques of Navigation in the Renaissance," in *Art, Science, and History in the Renaissance*, ed. Charles S. Singleton (Baltimore: Johns Hopkins Press, 1967), 187-237. Taylor, although widely cited, provides no scholarly apparatus and is sometimes erroneous; I have therefore consulted her work only as a guide to finding primary sources.

revolution. Other factors contributed to the upsurge in European exploration in the fifteenth and sixteenth centuries, of which only a few can be mentioned briefly.

No matter how great the potential payoff, expensive and risky voyages could not take place on a regular basis without surplus resources and a stable society. Life must have seemed uncertain in early modern Europe, with its religious wars, invasions of Turks, harvest failures, and outbreaks of plague and syphilis; nevertheless, it was wealthy and secure when compared with early medieval Europe and could well afford to build many ships even when a significant fraction met with disaster. Ideally, some mechanism would exist to distribute the risk among several investors. One such mechanism, the joint-stock company, appears in the last section of this chapter in the form of the Muscovy Company. Changes in ship design gave rise to entirely new kinds of ships built to withstand the rough waters of the ocean, including the celebrated Portuguese caravel. In contrast to oar-driven galleys, the new roundships had two or three masts rigged for sailing close to the wind. Requiring only a small crew, hence fewer provisions, they offered more room for cargo and provisioning for long voyages, and they could make progress on the ocean even in adverse winds.[11]

For voyages along the Atlantic seaboard or in parts of the Mediterranean, mariners of the later Middle Ages relied on coastal navigation, which is also called pilotage or coasting. Coastal navigation proceeds by experience and by observation of primarily terrestrial phenomena, such as rocks and tides. The navigator recognizes

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[11] J. R. S. Phillips, *Medieval Expansion of Europe*, discusses some of the factors necessary for an expanding society. Some of these factors came into play in the High Middle Ages; others, not until the fifteenth century. Keith Thomas, *Religion and the Decline of Magic* (New York: Charles Scribner's Sons, 1971), 3-21, paints a pessimistic picture of life in the early modern period. For more information on the changes in shipbuilding see Richard W. Unger, *The Ship in the Medieval Economy, 600-1600* (London: Croom Helm; Montreal: McGill-Queen's University Press, 1980).

features of the coast and knows how to steer the ship safely to the desired port. Precise observation of the heavens do not play a role in coasting, though mariners of the fifteenth century linked the Moon to tides and consulted the North Star to tell time and to check bearings.

The main tools of the coastal navigator were the compass, the lead and line, and the rutter. The use of the compass was introduced to Europe during the Middle Ages; before that time, naked-eye observations of Polaris and the rising and setting points of the Sun sufficed to find the cardinal directions. The lead and line is a weight with tallow attached for taking soundings. The line measures depth while the tallow brings up some of the material at the sea-bottom. The pilot looks for mud in one area and white shells in another. He also watches for headlands, dangerous rocks and shoals, and other distinguishing characteristics of a stretch of shoreline. These features would be collected, together with information about currents, tides, and bearings between ports, in a book of sailing directions called a rutter, a word related to the French *routier* or "route." Unique rutters were created as navigators recorded details of ports they visited. Other rutters giving directions for standard voyages circulated widely, including printed versions in the sixteenth century. Some may actually have been written for curious passengers rather than sailors.

Rutters and other paper materials on board ship had a hard life; frequent use and constant exposure to moisture ensured that most of them perished. However, an English rutter has survived from the early fifteenth century. The following extracts give directions for sailing near the southern and western coasts of England.

> All the havens be full at a west south west moone betwene the Start and Lisart, the Londis ende and Lisard lieth est southest and west northe west. At the Londis

> ende lieth Raynoldis stone. A litill birth [berth] of but xij. fadom shall lede you all be owten hym and south south west of the Landes ende lieth the gulf. the langshippis and the landende lien north northwest and south southest. . . . Among Opyn Lesarde is grete stone as it were benys [beans] and it is raggid stoon. . . .[12]

The sections of the rutter quoted above guide the ship from Start point (a headland on the south coast of Devon) around Lizard Point or Lizard Head (a promontory at the southern tip of England) to Land's End (the western tip of Cornwall near the Scilly Isles). An important piece of information given here is the "establishment of port." The spring tides, which are the highest tides at a port, occur at the new or full Moon, but the exact time of day when they reach their highest point varies between ports. Standard practice in the Renaissance was to give the establishment of port according to the bearing of the Moon. The bearing west-southwest in the rutter signifies 4:30 p.m. or a.m. From the spring tide, the time of high tide at other points in the lunar month could be calculated. The main hazards near Land's End are the Rundle Stone or Runnel Stone ("Raynoldis stone") and a group of rocks called the Long Ships. A separate section gives the typical sea-bed material; near Lizard Point, the lead and line will bring up coarse gravel the size of beans.[13]

This early English rutter illustrates the nature of coasting. The navigator must possess detailed knowledge of the coastline, gained through instruction and reading or by experience on previous voyages. Yet the knowledge is largely empirical. Lizard Point lies

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[12] *Sailing Directions for the Circumnavigation of England and for a Voyage to the Straits of Gibraltar (From a 15th Century MS.)*, ed. with account by James Gairdner and glossary by E. Dilmar Morgan (London: Hakluyt Society, 1889), 14, 21. Waters, *Art of Navigation*, 12 n. 1, gives a tentative date of 1408 for the manuscript but suggests that it is based on older information, which might have circulated in writing or orally.

[13] The places and landmarks are identified by E. Dilmar Morgan in the glossary to *Sailing Directions*, 27-37. The use of the compass and lunar bearings to tell time is explained in Waters, *Art of Navigation*, 31, who also identifies several of the times given in this rutter.

south-southeast of Land's End, but the rutter does not mention the latitude and longitude of either place. The navigator finds directions by the compass and observes the Moon only to find the tide. Pilotage, in short, is like following a recipe.

In the Mediterranean ships also crossed the open sea, which provided a different set of challenges. The visual cues of the shoreline were not available and the lead and line could not sound the deep sea basin. Navigators found their way with the aid of the portolan chart, a map showing coastal outlines drawn to scale. Superimposed on the map is a network of rhumb lines indicating the directions of the winds or the points of the compass rose. The navigator determines the direction to be sailed by identifying a rhumb line parallel to the course of the ship. During the voyage this direction is maintained with the aid of a compass. By estimating the distance covered and measuring along the rhumb line the navigator tracks the progress of the ship on the portolan chart.[14]

The technique of estimating direction and distance sailed, with or without charts, is called dead-reckoning; it worked well in the Mediterranean where a ship did not leave sight of land for more than a few days. English ships sailed to Portugal by dead-reckoning, since cutting across a small stretch of ocean made for a shorter voyage than following the coasts of France and Spain. A pilot skilled in dead-reckoning could even cross the uncharted waters of the Atlantic--Columbus may have relied on it in 1492--but not without risk. For regular voyages, especially across great stretches of water, it was simply too unreliable. As one navigator explained, "once one has committed an error, one

[14] The use of the portolan chart is explained in Randles, "From the Mediterranean Portolan Chart to the Marine World Chart of the Great Discoveries: The Crisis in Cartography in the Sixteenth Century," in *GCNS*.

can never get back on the course one had set."[15]

A third method of navigation using the stars was developed by Portuguese sailors at the end of the Middle Ages. Southern European deep-sea sailing began as it did in northern Europe with short steps between islands. A series of island chains led from the western coast of Africa well out into the Atlantic ocean: the Canaries, the Madeiras, the Azores. Although already inhabited, these islands were new to the Europeans who encountered them during voyages in the fourteenth and fifteenth centuries. The Canaries were known before 1341, when the Portuguese crown sponsored an expedition there; the Azores waited perhaps as late as 1427 for their discovery.[16] After their initial visit, however, the Portuguese left the Canaries alone for several decades, until they began a period of aggressive expansion in 1412.

Nineteenth-century narratives presented Portuguese expansion and the invention of new navigational techniques as a deliberate program guided by the enlightened Prince Henry (1394-1460), dubbed "the Navigator" for his supposed personal achievements in the new science. More recent studies have identified dynastic politics as a long-range factor in exploration.[17] A series of wars between Portugal and Castile provoked a

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[15] The quote is from the fifteenth-century navigator Diogo Gomes, translated in Randles, "The Emergence of Nautical Astronomy in Portugal in the XVth century," in *GCNS*, p. 47. For the use of dead reckoning between England and Portugal, see Waters, *Art of Navigation*, 37. For the difficulties of dead reckoning, including a skeptical assessment of its use by Columbus, see C. V. Sölver and G. J. Marcus, "Dead Reckoning and the Ocean Voyages of the Past," *The Mariner's Mirror* 44 (1958): 18-34.

[16] For Portuguese knowledge of the three groups of islands see Bailey W. Diffie and George D. Winius, *Foundations of the Portuguese Empire, 1415-1580* (Minneapolis: University of Minnesota Press, 1977), 27-29 (Canaries), 57-62 (Madeiras and Azores). Historians of exploration have long debated who made the discoveries and when, but settling such questions is irrelevant to my generalized account.

[17] My explanation of the political and economic motivations for Portuguese expansion is a greatly simplified version of the accounts in Malyn Newitt, "Prince Henry and the Origins of Portuguese Expansion," in *The First Portuguese Colonial Empire*, ed. Newitt (Exeter: University of Exeter, 1986), 9-35; and Diffie and Winius, *Foundations of Portuguese Empire*.

Portuguese civil war, ending in the coronation of João of Aviz in 1385. The new king, whose status as legitimate successor rather than usurper was questionable, needed to strengthen his power base among the lesser nobility and merchants, who had been his chief supporters in the civil war. Steeped in the ethos of chivalry, the Portuguese nobles considered their proper occupation to be war, which provided them a chance to earn honor and recognition as well as to enrich themselves.

Initially, ongoing wars with Castile kept the nobles occupied, but these came to an end in 1411. Almost immediately the crown began to prepare for a *reconquista* of Morocco. The nobles would be able to accumulate land and cash, both of which were in short supply in Portugal, while new markets would be opened for the merchants. On August 21, 1412, after a single day of fighting, the town of Ceuta fell to the Portuguese. The anticipated markets failed to materialize, however, because Muslim merchants redirected the trans-Saharan trade route to other ports. The costs of defending the city against besiegers led some to argue for its abandonment.

According to Portuguese historians, the expansion began as a justification of Ceuta when the king made it a staging area for expeditions along the coast of Africa. The newfound Madeiras became additional objects of Portuguese colonization a few years after the initiation of *reconquista*. Trips to the Azores and a failed attempt to conquer the Canaries followed. Many of the voyages were frankly piratical in nature: in the late fourteenth century great nobles began commissioning captains to sail privateers around the coast of Morocco. Prince Henry's modern epithet "the Navigator" derives in part from his sponsorship of ambitious pirates.[18] A further motive for exploration was the

[18] Newitt, "Origins of Portuguese Expansion," 19-21. State-sponsored piracy and privateering were characteristic features of international relations in the early modern world; Janice E. Thomson,

ongoing rivalry with Castile; both countries claimed possession to the Atlantic islands and competed in exploring the African coast.[19]

Recent scholarship has shown that Henry did not, as was once supposed, found a school of navigation at Sagres, invent new astronomical instruments or ship designs, or embark on his own voyages of exploration. Instead, he created conditions favorable to exploration and scientific study that led accidentally to new developments in navigation. A letter from Poggio Bracciolini includes the sort of praise that biographers once mistook for a description of Henry's personal achievements:

> How illustrious indeed to have been the only one of such courage, of such resolution and of such planned purposefulness to have dared to do that which none so far had undertaken or attempted. You alone [have discovered] unknown seas in regions never seen, unknown races living outside the known world and savage peoples living at its farthest confines beyond the regular annual shifts of the sun's track, where none before had opened a way.[20]

Modern historians, eager to correct old misreadings, regard the panegyrics of Henry's biographers as propaganda. Renaissance readers would have understood them as the rhetoric of patronage.

The new destinations of the Portuguese posed two difficulties for navigators.[21]

Mercenaries, Pirates, and Sovereigns: State-Building and Extraterritorial Violence in Early Modern Europe (Princeton: Princeton University Press, 1994).

[19] Carla Rahn Phillips, "Exploring from Early Modern to Modern Times," in *Maritime History as World History*, ed. Daniel Finamore (Salem: Peabody Essex Museum; Gainesville: University Press of Florida, 2004), 68.

[20] Translated in Randles, "The Alleged Nautical School Founded in the Fifteenth-Century at Sagres by Prince Henry of Portugal, Called the 'Navigator,'" in *GCNS*, 13 (bracketed words added by translator). For historiographies of the critical reassessment of Prince Henry see also Diffie and Winius, *Foundations of Portuguese Empire*, chapter 7, "Henry 'the Navigator' Who Followed His Stars," 113-122; and P. E. Russell, *Prince Henry the Navigator: The Rise and Fall of a Culture Hero* (Oxford: Clarendon, 1984). The practice of ascribing scientific discoveries to their patron is discussed in Mario Biagioli, *Galileo, Courtier: The Practice of Science in the Culture of Abolutism* (Chicago: University of Chicago Press, 1993).

[21] For an English-language summary of the literature on the Portuguese introduction of astronomy to navigation see Randles, "Emergence of Nautical Astronomy," in *GCNS*.

Sailing to the Azores or Madeira meant that ships had to find small islands in a large body of water and return to home port. On the other hand, the rocky African coast proved to be largely featureless when viewed from ship, in contrast to the diversity presented by the European shoreline. Navigators found a solution by substituting the heavens, which provided a fixed reference point available to all, for the local reference points used in coastal navigation. Navigation by the stars--nautical astronomy--required that the practitioner be able to use astronomical instruments and understand enough theory to make and interpret observations. Mariners first consulted the stars in conjunction with the portolan chart, which had been extended to include the known part of the African coast, as a means of checking distance estimated with dead-reckoning. The first known use of an astronomical instrument took place on board ship during a voyage in 1460-62, when a navigator used a quadrant to measure the elevation of the celestial pole.[22]

Initially, the quadrant was not used to determine latitude in the sense of an absolute location on the globe. The quadrant indicated the altitude of the North Star at important ports such as Lisbon (a common home port for Portuguese ships); the navigator determined the relative position of the ship in order to correct position on the portolan chart. Latitude, as a measure of degrees, was not used in early astronomical navigation, and portolan charts of the fifteenth century did not include grids of latitude.[23] Measuring the altitude of the pole in degrees became important in the sixteenth century when "sailing down the latitude" became standard practice. In latitude sailing the ship travels

[22] Randles, "Emergence of Nautical Astronomy," in *GCNS*, 47-48. The recollections of the navigator, Diogo Gomes, are recorded in *Reportorio dos Tempos*, published by Valentim Fernandes in 1518.

[23] Some portolan charts included latitude notations in the borders, according to John Rennie Short, *Making Space: Revisioning the World, 1475-1600* (Syracuse: Syracuse University Press, 2004), 19, but navigators did not fix their positions in terms of latitude.

north or south until reaching the desired latitude, then sails east or west along the parallel, steering its course with the compass and correcting latitude from time to time.[24] The discovery of the Atlantic wind system in the 1490s encouraged this sort of sailing and made routine transatlantic expeditions possible; ships intending to cross the Atlantic traveled south to the dependable winds near 40° latitude.[25]

The elevation of Polaris above the horizon did not indicate the exact latitude of the ship, since the star was located about 3 1/2° from the north celestial pole. Navigators corrected their observations with the "Regiment of the North Star." Two stars in the "bowl" of the Little Dipper were known as the Guards; as the sphere of fixed stars made its daily rotation, the Guards appeared to move in a circle around Polaris. The observer pictured a man in the sky, with his arms held out and his navel near the pole: the position of the Guards near the man's head, feet, or arms made known the necessary correction. Eventually the man was replaced by a compass rose, but the principle remained constant. Martín Cortés, author of the important Spanish navigational textbook *Breve compendio de la sphera y de la arte de navegar* (first edition 1551), created a simple paper computer that showed *Ursa minor* as a horn rotating around the North Star.[26]

As Portuguese ships neared the equator in the early 1470s, they found that Polaris sank to invisibility near or below the horizon. In its place mariners turned to the Sun for

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[24] The first chart with latitude marked for latitude sailing is Portuguese and dates to about 1500; Waters, "Navigation in the Renaissance," 219-220.

[25] Felipe Fernández-Armesto, "Maritime History and World History," in *Maritime History as World History*, ed. Daniel Finamore (Salem: Peabody Essex Museum; Gainesville: University Press of Florida, 2004), 30.

[26] Martín Cortés, *The Arte of Navigation, Conteynyng a compendious description of the Sphere, with the makyng of certen Instrumentes and Rules for Navigations: and exemplified by manye Demonstrations. Written in the Spanyshe tongue by Martin Curtes, And directed to the Emperour Charles the fyfte. Translated out of Spanyshe into Englyshe by Richard Eden*, (London: Richard Jugge, 1561), fol. 74r-76r.

determining latitude. First the navigator must determine the local meridian: the great circle passing through the pole and the zenith. The simplest way to do this was to find south with a compass, though later authors recommended that navigators follow more complicated but accurate procedures.[27] At noon he measures the altitude of the Sun as it crosses the meridian. He then consults a set of tables of declination called the "Regiment of the Sun." The ecliptic was tilted about 23;30° with respect to the celestial equator in the sixteenth century; on every day except the equinoxes, therefore, the Sun reaches a different angular distance from the equator, and it is this value the navigator requires. Some manuals of navigation give the declination for each day; others give the solar longitude as the "place of the Sun" in one of the zodiacal signs. In the latter system, the navigator then enters a second set of tables with the place of the Sun to find the declination. Finally, with a formula he calculates the latitude from the declination and altitude of the Sun.[28]

While the first instrumental observations of altitude at sea were made with a quadrant, later navigators preferred the astrolabe and the cross-staff. The astrolabe had a long history as an astronomical instrument. Sailors preferred to hold the astrolabe by hand while making observations, and steady it against the rolling motion of the ship, but this could be difficult and tiresome with a full-sized metal astrolabe. Navigators therefore

[27] William Bourne gives instructions for finding the meridian in *A Regiment for the Sea* (first edition 1574); see Bourne, *A Regiment for the Sea and Other Writings on Navigation*, ed. E. G. R. Taylor (Cambridge: Cambridge University Press, 1963), 209-212.

[28] The use of the Regiment of the Sun, following tables in Abraham Zacuto's *Almanach Perpetuum* (published in Portuguese in 1496), is summarized in Randles, "Emergence of Nautical Astronomy," in *GCNS*, 50-51. Randles omits the step of determining the meridian, which was not mentioned by all authors. For an example of the two-table method see Cortés, *Arte of Navigation*, and the example in this chapter; for the one-table method with yearly almanacs, see Bourne, *Regiment for the Sea*.

used a mariner's astrolabe or ring, which received the latter name because it is little more than a graduated metal ring with an alidade for sighting the Sun or North Star. The cross-staff is a long stick with a moveable cross-piece. The observer holds the end of the staff near one eye and slides the cross-piece until it subtends the angle between the star or Sun and the horizon. Altitude can then be read from markings on the staff. William Bourne explained why the navigator should be acquainted with both instruments in the first original English navigational treatise, *A Regiment for the Sea* (1574):

> To take the true heigth of the Sunne at the Sea, the beste way is, to doe it with the crosse staffe: for that the Sea is moueable, and causeth the Shippe to heaue, and sette little or much: and also vpon the crosse staffe the degrees be larger marked than the Ring or Astrolobe: and in a large instrument an errour is seene sooner and better than it is in a small instrument. . . . it is beste to take the heigth of the Sunne with the crosse staffe, when the Sunne is vnder 50. degrees in heigthe aboue the Horizon, for two causes. The one is this: till the Sunne be .50. degrees in heigthe the degrees be largely marked vppon the crosse staff, but after . . . they be lesser marked. The other is, [that] if it dothe exceede .50. degrees, then by the meanes of casting your eye vpwardes and downwardes so muche, you may soone commit error. . . .[29]

Bourne's description implies a geographical division of use. The Sun is most likely to have a meridian altitude over fifty degrees near the equator, and so sailors there must have had frequent recourse to the astrolabe, while ships sailing in north Atlantic waters could have steered by the preferable cross-staff. The converse would be true in the case of determining latitude by Polaris, though the authors of navigational textbooks preferred the Regiment of the Sun.

To illustrate how oceanic navigation proceeded aboard ship, let us consider the hypothetical example of a progressive English pilot who wishes to find the latitude of his ship on June 24, 1567. A treatise on nautical astronomy has recently been translated into

[29] Bourne, *A Regiment for the Sea*, 207-208.

English. It is Cortés' *Breve Compendio*, which was Englished as *The Arte of Navigation* by Richard Eden in 1561. The circumstances of its translation will be discussed in the next chapter; for now, it will provide us with an example of a general practice. The pilot consulting his book reads that "To knowe the altitudes by the Sunne, three thynges are necessary. That is to saye, an instrument, the declination of the Sunne, and rules."[30]

Step 1: Measure the meridian altitude of the Sun. Cortés recommends an astrolabe for measuring the Sun's altitude and a cross-staff for measuring the elevation of Polaris. Unlike Spanish mariners who most often worked in lower latitudes, English navigators were apt to switch the instruments when they found themselves in northern waters. We shall assume, however, that the ship has sailed close to the equator, and so our pilot chooses the astrolabe. Observing the Sun for an interval of time in order not to miss local noon, he finds its maximum altitude to be 82°. In fact, the Sun crosses the meridian to the north of the zenith, meaning that the ship has passed south of the Tropic of Cancer. In high summer at this latitude, shadows are cast to the north.

Step 2: Find the declination of the Sun. Turning to his book, the pilot reads the rules for finding "the true place of the Sunne in the Zodiack."[31] First he consults "The Table of the true place of the Sunne" and finds that on June 24, the Sun is in 11;46° of Cancer. Next he consults "The Table of the Equations of the Sunne," which gives year-by-year values to be added to the true place of the Sun. In the year 1567 the equation is 0;39°. The Sun's location in the zodiac differs from the place given in the first table for

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[30] Cortés, *Arte of Navigation* (1561), fol. 68r. Instructions for making and using an astrolabe follow in part 3, chapter 7, fol. 68v-71r.

[31] Title of Part 2, chapter 3 in Cortés, *Arte of Navigation* (1561), which combined with the following chapter explain how to find the solar declination with tables (fol. 23v-27r). I have omitted the cruder method employing a paper computer.

two reasons: the six-hour difference between the tropical and calendar years caused by rounding days; and the smaller difference caused by precession and trepidation (Cortés accepts the theory of the Alfonsine Tables). Thus the equation changes regularly over a four-year cycle (decreasing by a quarter degree each year, to accommodate the extra quarter day) but increases slightly every four years. However, a third step is needed to find the Sun's place; because 1567 is a common year rather than a bissextile (leap) year and the date is after the end of February, 1° must be subtracted from the value in the first table. In a bissextile year the Sun would have moved about a degree on February 29, but a common year is one day shorter.

Taking the original value of 11;46°, the pilot adds 0;39° and then subtracts 1° to find that the current place of the Sun in the zodiac is 11;25° of Cancer. In the next chapter he finds a table giving the solar declination for each whole degree of the zodiac. The declination when the Sun is in 11° of Cancer is 23;3°, and at 12° it is 22;57°. Cortés gives the navigator two options: he may simply take the declination for the nearest whole degree as found in the table, or he may find the declination more accurately by taking a value between the two declinations which is proportionate to the number of minutes in the place of the Sun. A lazy pilot would be content to accept the value of 23;3° from the table, but ours is enamored of accuracy and decides to make the extra calculation. Since the place of the Sun is about eleven and a *half* degrees, he must find the value *halfway* between the declinations for eleven and twelve degrees. Subtracting the smaller from the larger, he finds that the difference between them is six minutes. One half of this is three minutes. Taking three minutes from 23;3°, he finds that the declination of the Sun at noon on June 24, 1567, is 23° exactly.

Step 3: Calculate the ship's latitude from the Sun's altitude and declination. For finding latitude Cortés gives four sets of instructions based on location and time of year. The pilot reads through the rules until he finds a description of his own situation: "When the Sunne declyneth from the Equinoctial towarde the one pole, and the shadowes shalbe towarde the other, we shall ioyne the declynation with the Meridiane altitude."[32] In June the Sun is to the north of the equinoctial, and as the navigator noted in the first step, shadows fall to the south. He adds 23° (the declination) to 82° (the altitude) to get 105°. The rule tells him that if the total exceeds 90° "then the ouerplus of 90. shall we bee distaunt from the Equinoctiall towarde the pole where the Sunne declyneth." The ship is at 15° north latitude.

By the middle of the sixteenth century the best navigators were, in fact, practicing astronomers who handled common astronomical instruments and calculated the position of the Sun from planetary tables. Any country aspiring to be a competitive sea power needed skilled navigators with knowledge of mathematics. As we shall see, England had fallen behind by the Elizabethan period. As advocates of educational reform were fond of pointing out, the country relied heavily on the older technology of pilotage while its chief rival, Spain, prospered from its adoption of nautical astronomy. The problems of navigation contributed greatly to the English revival of astronomy. First, however, we shall consider the state of mathematics education in England in the early sixteenth century.

[32] Cortés, *Arte of Navigation* (1561), fol. 71v.

Astronomy in Early Tudor England

Printing was introduced to England by William Caxton (1415/24-1492), who first published *The dictes or sayengis of the philosophhres* in 1477.[33] In the first half of the sixteenth century, astronomy could be found in English printed books only in the more rudimentary handbooks. For astronomy at the level of a *theorica* or even a good *sphaera*, English readers relied on manuscripts and on printed books imported from the continent. Concerned individuals were well aware of their island's dependence on other countries not only for mathematics but for many fields of knowledge, and for skilled artisans as well; they urged or attempted to implement educational reform and called for or prepared translations and new works written in English to reach a broad audience.[34] Among them was a group of humanists connected to Thomas More (1477/78-1535) with a strong interest in the revival of Greek knowledge, including mathematics. Simon Grynaeus, whom Melanchthon addressed in his preface to Sacrobosco's *Sphaera*, met the More circle when he visited England in 1531. Grynaeus dedicated three of his publications to men he met in England: a Greek edition of Euclid, in 1533, dedicated to Cuthbert Tunstall, one of the More humanists; a Greek edition of Plato and related works in 1543, dedicated to Thomas More's son John; and the first Greek edition of the *Almagest* in 1538, dedicated to Henry VIII.[35]

John Rastell (ca. 1475-1536), More's son-in-law, wrote a play in the early 1520s

[33] For biographical information on Caxton, see *Oxford Dictionary of National Biography in Association with the British Academy: From the Earliest Times to the Year 2000*, ed. H. C. G. Matthew and Brian Harrison (Oxford: Oxford University Press, 2004), 10:694-98. (Series subsequently abbreviated as *DNB*.)

[34] Johnson, *Astronomical Thought in Renaissance England* is the standard survey (Caxton's first publication is mentioned at 69-70); Louis Wright, *Middle-Class Culture in Elizabethan England*, describes efforts to improve education for a broader time period than the title suggests.

[35] For the More circle and Grynaeus' connection to it, see Johnson, *Astronomical Thought*, 82-87.

titled *A new interlude and a mery of the nature of the .iiij. elementes* intended to help satisfy the need for basic educational material and, at the same time, inspire curiosity and the desire for more information. The play provided instruction in cosmography but also advocated the production of further texts in the vernacular:

> The grekes the romayns with many other mo
> In their moder tonge wrot warkes excellent
> Than yf clerkes in this realme wolde take payn so
> Consyderyng that our tonge is now suffycyent
> To expoun any hard sentence euydent
> They myght yf they wolde in our englyshe tongue
> Wryte workys of grauyte somtyme amonge
> For dyuers preugnaunt wyttes be in this lande
> As well of noble men as of meane estate
> whiche nothynge but englyshe can understande
> Than yf connynge laten bokys were translate
> Into englyshe/wel correct and approbate
> All subtell sciens in englyshe myght be lernyd
> As well as other people in their owne tonges dyd.[36]

In this case, humanism manifests as education in the common language. For the ancients, the common language was Greek and Latin, but with time it had become English, so translation has become a more appropriate course of action than expecting universal knowledge of ancient tongues.

Rastell identifies an audience composed of two groups, both "noble men" and those "of meane estate." He contrasts both with the clerks, who study Latin at university and possess the skills needed to translate textbooks. The relationship between nobles and gentlemen on the one hand, and commoners on the other, was a favorite theme of Tudor educational reformers. Neither group intended to complete a university degree and neither was likely to read comfortably in Latin. Yet members of both groups might find

[36] John Rastell, *A new interlude and a mery of the nature of the .iiij. elementes*. (London: J. Rastell, ca. 1520), fol. A2r-v.

themselves engaged in tasks calling for the application of mathematics, even interacting on such tasks. For instance, a gentleman placed in command of a ship might wish to check on the navigation of the pilot, or a well-to-do landowner would survey his estates using instruments prepared by craftsmen.[37] Mathematicians throughout the Tudor period considered these two groups to make a natural combined audience far more likely to read English than Latin.

Early printed works on nature in England included the heavens as one of several topics to be given superficial coverage, placing them in the category of encyclopedias or handbooks of cosmography. Rastell's play "declar[ed] many proper poyntes of phylosophy naturall/and of dyuers straunge landys/and of dyuers straunge effectes & causis" including meteorology and the creation of stones, metals, plants, and herbs. Since the entire play would "conteyne the space of an hour and a halfe," any one subject could receive only the scantest of introductions.[38] The earliest book in this class was *The Myrrour of the World* (first edition 1481), a translation by Caxton of the thirteenth-century work *Image du monde*. The *Myrrour* contains three parts: one on the liberal arts and basic cosmology; the second on natural history; and the last on astronomy.[39] Another popular work was *The Kalender of Shepherdes*, translated from *Le Compost et Kalendrier des bergiers* by three different translators in 1503, 1506, and 1508; it remained in print well into the seventeenth century. Through the vehicle of a conversation between unlettered yet remarkably well-informed rustics, the *Kalender*

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[37] A. J. Turner, "Mathematical Instruments and the Education of Gentlemen," *Annals of Science* 30 (1973): 51-88.

[38] Rastell, *New interlude*, fol. A1r-v (quote and list of subjects).

[39] Caxton, transl., *Hier begynneth the book callid the myrrour of the worlde* (Westminster: William Caxton, 1481). For the background to the *Myrrour* see Johnson, *Astronomical Thought*, 70-71.

teaches basic astronomy, astrological medicine, and religion. The first part was also extracted and printed separately as *The Compost of Ptolemy*.[40]

Publishers of the *Myrrour* and the *Kalender* aimed for a popular market, not mathematical practitioners. The astronomy in both works is even simpler than Sacrobosco's *Sphaera*, which in many universities was routinely read by all students. Books in this class typically explain the arrangement of the heavens and Earth, the celestial and terrestrial circles, demonstrations of the shape of the Earth, the daily rotation, and the causes of eclipses, while shortchanging more challenging or tedious mathematical subjects such as the climes and celestial measurements. The table of contents for the *Myrrour* lists a chapter with the promising title of "Wherfor and why the world was mesured." Turning to the chapter, the reader learns that "auncyent philosopres" measured the circumference and diameter of the Earth and used the results to measure the sizes and distance of the planets and stars, finding that only Venus, Mercury, and the Moon were smaller than the Earth. After promising to reveal celestial distances, the book enters a long digression on ancient philosophy and the invention of money. Finally returning to the topic of measurements, the *Myrrour* says that the ancients "mesured it [the Earth] rounde aboute lyke as they sholde haue compassed it al aboute wyth a gyrdle," fixing its circumference at 20,427 miles and its diameter at 6,500 miles. These measurements are on the same order of magnitude as standard measurements of the day; the author or translator had access to Ptolemaic measurements, but omitted or could not understand how astronomers arrived at them. Further chapters provide the sizes of the Moon and Sun. The great distance of the stars is illustrated by the time it would

[40] The edition I consulted is *The kalender of shepeherdes* (London: Winken de Worde, 1528). For the publishing history of the *Kalender* see Johnson, *Astronomical Thought*, 72-75.

take for Adam to walk to the starry sphere or for a stone to drop from the stars to Earth, but no value is given for the distance itself.[41]

[41] Caxton, transl., *Myrrour of the worlde* (1481), fol. k6v-k7r, m2r-m4r.

The First Printed English *Sphaeras*

Two English-language *sphaeras* first saw print in the 1550s. The better known is Recorde's *Castle of Knowledge*; however, I shall begin with the more obscure, earlier work, a translation of Proclus' book on the sphere by William Salesbury (a. 1520 - ca. 1580), who was not a mathematician but a Welsh translator. In a prefatory letter to the translation he addresses his cousin John Edwardes, who had requested an English book "on the Sphere of the worlde."[42] He claims to be as ignorant of astronomy as of Latin and English. Setting aside his self-deprecatory assessment of his linguistic abilities, we may accept his explanation of the project at face value: he translated no other astronomical works and apparently was uninterested in mathematics. Edwardes' request confirms the assertions of mathematical advocates that gentlemen would study astronomy if English textbooks could be made available.

Salesbury's account of his search for a book to satisfy his cousin's wish provides a valuable glimpse of the market for astronomical books in England at mid-century.

> I walked my selfe, rounde aboute all Poules Churche yearde, from shop to shop, enquyrynge of suche a treatyse neyther coulde I here of any that eyther wrote of this matier proposely, nor yet occasyonallye. But what trowe you dyd I than by my fayth syr, I returned backe euen the same way (but wondrynge moche at the happe) and asked agayne for the same workes in laten, whereof there were .iii. or .iiii. of sondrye Aucthoures, brought, and shewed unto me, amonge all whiche (for the breuyte and playnes) I chose Proclus his doynge.[43]

The book Salesbury settled on was a Latin translation of Proclus (410-485) by Thomas Linacre (ca. 1460-1324), a medical humanist who taught Thomas More. Though not regarded today as his most significant work, Linacre's translation (first edition 1499) was

[42] Salesbury, "The Epystle," in Proclus, *The Descripcion of the Sphere or Frame of the worlde* (London: Robert Wyer, 1550), fol. A2r. On Salesbury, see *DNB* 48:696-99.

[43] Proclus, *Sphere*, fol. A2r-v.

his most popular publication in the sixteenth century and went through many editions in different countries.[44] We can only speculate why Salesbury, who distances himself from the translation and bemoans Linacre's failure to English the text, did not send his cousin a popular work such as the *Kalender of Shepherdes*. Possibly he considered them to lack the authority of a classical author or had in mind a book more focused on astronomy. The booksellers' stocks of Latin books almost without doubt included Sacrobosco's *Sphaera*, but he might have passed over it in favor of Proclus as a shorter work. I discuss other possibilities in the context of Recorde's astronomy below.

Salesbury's translation of Proclus contains seventeen chapters on the axis and circles of the world; in essence, it is an explanation of what an armillary sphere represents. It includes a modicum of technical information about the length of the longest day and the appearance of certain stars at different parallels. Three chapters not in the table of contents have been added, on bleeding, bathing, and sowing according to the location of the Moon in the zodiac. It includes only one of the eight astronomical propositions listed by Maestlin (discussed in chapter two above), namely, that the heavens are spherical, and does not provide supporting evidence. A more in-depth treatments of cosmology could be found even in the *Myrrour of the worlde*. The *Sphere* of Proclus nevertheless deserves remark as the first printed English book to be devoted entirely to astronomy and the use of one of the chief mathematical instruments.

Soon after the publication of Proclus' *Sphere*, an English book of astronomy appeared that was comparable to the *sphaeras* of Sacrobosco and contemporary

[44] On Linacre, see *DNB* 33:803-806; and *Essays on the Life of Thomas Linacre ca. 1460-1525* , ed. Francis Maddison, Margaret Pelling, and Charles Webster (Oxford: Clarendon Press, 1972). The editors' introduction connects Linacre with More and his circle on page xx. On the popularity of his Proclus translation see page 292. While the article on Proclus in *DSB* treats the *Sphere* as a genuine work of

continental authors, written by the mathematical textbook author Robert Recorde (ca. 1510-1558). Recorde received a B.A. Oxford in 1531 and an M.D. from Cambridge in 1545. Soon after earning his degrees he began practicing medicine in London. He served as comptroller of the Bristol mint in 1549 and surveyor of mines and monies in Ireland from 1551 to 1553. In 1556 he renewed a quarrel with the earl of Pembroke, who successfully sued him for libel. Recorde was subsequently imprisoned, possibly for not paying the earl, and died in June of 1558, still in prison. [45]

Recorde published one book on medicine, *The Urinal of Physick* (first edition 1547), and four surviving mathematical textbooks. *The Ground of Artes*, his arithmetic, was first published in 1543. It was preceded by an English arithmetic, *An Introduction for to Lerne to Recken with the Pen, or with the Counters* (first edition 1537). Possibly compiled, like the *Myrrour* and the *Kalender*, from French sources, this earliest printed arithmetic went through eight editions by 1629. Though mildly popular, it could not compete with the *Ground of Arts*, which was revised by Recorde for a 1552 edition and after his death by other authors, including the famed Tudor mathematician John Dee (who is discussed in the next chapter), with a final edition appearing in 1699. It was the most widely read and influential English textbook on arithmetic in the early modern period.[46]

Recorde's other three known textbooks are *The Pathway to Knowledge* (first edition 1551), on geometry; *The Castle of Knowledge* (first edition 1556), on astronomy;

Proclus, the authors of the anthology regard it as spurious.

[45] For biographies of Recorde see Frances Marguerite Clarke, "New Light on Robert Recorde," *Isis* 8 (1926): 50-70; *DSB* 10:338-40; and *DNB* 46:246-48.

[46] Joy B. Easton, "The Early Editions of Robert Recorde's *Ground of Artes*," *Isis* 58 (1967): 515-32; A. W. Richeson, "The First Arithmetic Printed in English," *Isis* 37 (1947): 47-56.

and *The Whetstone of Witte* (one edition in 1557), on arithmetic and algebra. The *Castle* lays out a course of reading for mathematical students, who are to begin with the *Ground of Artes* (arithmetic), proceed through the *Pathway* (geometry), *The Gate of Knowledge* (a book on mensuration and the quadrant, now lost and perhaps never published), and the *Castle* (astronomy), and conclude with *The Treasure of Knowledge* (possibly a book on the second part of astronomy, the traditional culmination of the mathematical textbook sequence). Recorde envisioned further works on mathematics, history, and natural history, none of which have survived; it is doubtful that he finished them.[47]

The title-page of the *Castle of Knowledge* symbolizes the ordered nature of the heavens. In the center of the page stands the astronomical castle, surmounted by an enthroned king who may be Ptolemy.[48] Small figures in turrets below him observe the Sun and Moon with quadrant and astrolabe. At the left hand of the king, a blindfolded woman in tattered dress balances on a ball while tugging a string that turns “The wheele of Fortune whose ruler is Ignorance.” To his right, a classically dressed woman stands firmly on a block. In one hand she displays a compass; in the other, she holds aloft an armillary sphere labeled “The Sphere of Destinye whose gouernour is Knowledge.” A poem contrasts the two figures:

> Though spitefull Fortune turned her wheele
> To staye the Sphere of Vranye,
> Yet dooth this Sphere resist that wheele,

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[47] For descriptions of the surviving books see Easton, “A Tudor Euclid,” *Scripta Mathematica* 27 (1966): 339-55; Louise Diehl Patterson, “Recorde’s Cosmography, 1556,” *Isis* 42 (1951): 208-218; and Louis C. Karpinski, “The whetstone of witte (1557),” *Bibliotheca Mathematica*, 3rd ser., 13 (1912-13): 223-28. The reading program is in Recorde, *Castle* (1556), fol. a8r. Patterson’s summary of the *Castle* should be used only with caution. Even the title is misleading, since Recorde clearly excludes from the *Castle* material that he deems better suited to a cosmography.

[48] Iconographically, Ptolemy appears as a king for two reasons. First, he is the prince of astronomers. Second, a belief arose in the Middle Ages that he was a member of Egyptian royalty because of the shared family name Ptolemy. He is a monarch both literally and figuratively.

And fleeyth all fortunes villanye.
Though earthe do honour Fortunes balle,
And bytells blynde hyr wheele aduaunce,
The heauens to fortune are not thralle,
These Spheres surmount al fortunes chance.

Whereas the uneducated regard uncertain Fortune as the reigning force, friends of knowledge understand the regular, predictable progress of the heavens thanks to the sound foundation of astronomy. Recorde's vague formulation leaves the reader wondering to what degree "The Sphere of Destinye" affects humanity. Does it give history an inexorable push in the direction of its Fate by dispersing its astrological influences through the terrestrial realm? Or does it give us an example to follow by holding itself aloof from the vagaries of Fate?

The preface to the reader enumerates the benefits of astronomy enjoyed by all, while simultaneously insisting that it is an elite form of knowledge that leads to awareness of God. Recorde hymns the strange and imperishable stars that demonstrate the power of their creator. The ability to look and wonder is accessible to all, since men were given eyes to look at the stars (a quote from Plato popular amongst mathematicians of the time). Yet the heavens contain privileged information, for "in that boke who rightly can reade, to al secrete knowledge it will him straighte leade."[49] The star that appeared at the time of Christ's birth was visible to all, but only the wise men discerned its meaning. Before the Flood, God spoke to Noah directly, but he also placed warnings in the heavens so that a few people in other nations would have the opportunity to interpret them and warn their people to change their behavior. Recorde declines to enumerate all the instances of changes in empire, deaths of rulers, and other disasters presaged by the stars,

[49] Recorde, *Castle* (1556), fol. a4v.

both because they are so numerous and because “thei appertain to the Iudicial parte of Astronomy, rather than to this parte of the motions.”[50] Like most Christians of his time, Recorde adheres to a non-deterministic interpretation of astrology. God warns humanity in order that they have the opportunity to repent, but neither he nor they are bound by the signs of the stars.

Astronomy also serves practical uses. The physician turns to astronomy to identify critical days, treatments, and regimens. The farmer decides when to sow and harvest by the risings and settings of stars, indeed, he carries out all agricultural activity in accord with the celestial bodies. The shipmaster steers his course with instruments constructed on astronomical and cosmographical principles. The calendar would become hopelessly confused without astronomy, and must be reformed with its help. Proper time-reckoning serves not only the Church calendar, but the civil calendar and the study of history. Astronomy is an aid to sundry other arts as well.

Recorde concludes the preface by returning to his opening subject, religion. Above all other reasons, astronomy is to be studied because Christ has testified that his return would be heralded by signs in the heavens. Last of all he reminds his readers:

> The Sonne, the Moone and the Starres, were ordained of God to serue all nations that be vnder the heauens, as Moses dooth testifie. Then seynge God hath made them for mannes commoditie, and to be distincters of times, and for signes and tokens, for aide of mennes knowledge, let not men be vnkinde to God again, but lyfte vp their eies to heauen and beholde the good guiftes of God: Note diligently their meruailous motions, and studiouslye considre their wondrefull alterations, with perpetualle constancye and inuiolable ordre: so shall men neuer bee doubtfull of Goddes prouidence towarde them. . . .[51]

[50] Recorde, *Castle* (1556), fol. a5r. See chapter two above for the formulaic distinction between astronomy and astrology Recorde uses here.

[51] Recorde, *Castle* (1556), fol. a7r-v.

In fact, Recorde ends the *Castle of Knowledge* with an endorsement of astronomy even stronger, if possible, than his preface: "there was neuer any good Astronomer, that denyed the Maiestie and prouidence of God, though many other denyed bothe. . . ."[52] Unlike the clichés of astronomical apologetics that fill the rest of the preface, such as the references to astronomical passages in Scripture and Plato, the linkage of astronomy and providence is rare. As far as I have been able to determine, it has been identified previously only in the works of Melanchthon and his followers among the Lutherans.

Compare the above statements by Recorde to the following passage from the preface to an arithmetic textbook published at Wittenberg in 1536:

> These [Holy Scriptures] prove clearly that the sun, the moon and the other stars are true and enduring works of God, and the Holy Scriptures add for what purpose the heavenly lights are made: Let them be signs and set apart the seasons and the years. Although this description is rather short, it nevertheless contains great things and approves the study of astronomy. . . . It is therefore evident that it is considered good by God and that the observation of the movements of the heavens is enjoined. For, apart from bringing great benefit to universal life, this most beautiful order of movements also reminds us that nature does not exist by chance, but is created and governed by an eternal mind. Hence it strongly confirms in the mind worthy beliefs about God and providence.[53]

Recorde was familiar with at least one of Reinhold's works, possibly two; the full extent of his reading in astronomy is impossible to judge since he habitually names authors but not titles. The word "providence" suggests Lutheran influence in his thinking about the religious implications of astronomy. In the absence of a confirming statement or another point of similarity, such as a reference to Epicureans, the parallels are merely strongly

[52] Recorde, *Castle* (1556), 294.

[53] Melanchthon, *Orations*, 94 (transl. Salazar). See my comments on the authorship of this preface in chapter two above. I chose this passage for comparison with Recorde because it concisely expresses Lutheran sentiments (the stars are both beneficial to life and a sign of orderliness), not because I believe Recorde necessarily had it in mind when writing his own preface.

suggestive.

Let us proceed to a consideration of the organization of the *Castle of Knowledge*, which contains four chapters. The first chapter is a brief introduction to cosmology and the two "spheres," namely the celestial sphere and the armillary sphere. The second chapter gives instructions and plans for constructing two types of armillary sphere: the more familiar "ring" sphere reproducing the cosmos in skeletal form and the "solid" sphere showing the placement of stars on the eighth orb. The third chapter explains the use of the armillary sphere with sample problems. The final chapter reprises the subject matter of earlier sections in greater detail, with the addition of "demonstration or other certaine proofe" and of astronomical and trigonometrical tables. Recorde stressed the order of teaching in his approach to pedagogy, returning to the same topics in order to reinforce recently-learned material and also to deepen the student's understanding. In the *Castle*, this meant beginning with an outline of the "principall partes of the worlde" that the student could readily grasp and remember. Later, each part is revisited with the addition of demonstrations and problem-solving techniques.[54]

The *Castle* shares with some of Recorde's other works the format of a dialogue between the "Master" and the "Scholar." The book opens with the puzzled Scholar asking his teacher for assistance: he has read several books on cosmology but fears he cannot understand them. Here and throughout the book, the interlocutors discuss the strengths and weaknesses of various authors, perhaps in anticipation that the reader will eventually be wandering, like Salesbury, through the bookstalls of London without a living guide.

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[54] Recorde, *Castle* (1556), fol. a1v (table of contents), pp. 2-3 and 5-6 (order of presentation discussed). He also provides numbered summaries at the end of every chapter. See also Francis R. Johnson and S. V. Larkey, "Robert Recorde's Mathematical Teaching and the Anti-Aristotelian Movement," *Huntington Library Bulletin* 7 (1935): 59-87.

These discourses are an invaluable source of information about the availability of astronomical works in England at mid-century because Recorde never traveled to the Continent. He is unusually candid in expressing his opinions concerning a book's value and does not hesitate to warn novices away from certain texts.

By combining the appraisals with quotes and citations, it becomes possible to identify the main sources underlying the *Castle* and to separate them from works Recorde had read but not used extensively. The Scholar names three books on the sphere he had read before approaching the Master: Proclus' *Sphere*; Sacrobosco's *Sphaera*; and a third widely read introductory work, the *Cosmographia* of Orontius (Oronce Finé or Fine, 1494-1555). Later, when asked about his preparatory reading, the Scholar explains that of the great number of *sphaeras* in circulation, these three had the best reputation. The Master praises his decision but emphasizes that more reading is necessary. The first author he names is Cleomedes, with a warning that his work (the *Circular Theory of the Heavens*) should be read in the original Greek, not in the "much corrupted" Latin translation.[55] These four might be regarded as the cornerstones of the "castle," since they are Recorde's favorite authorities for beginning astronomical studies. His evaluation of the Cleomedes translation shows that he expected part of his audience readers to have at least a passing familiarity with classical languages; when he quotes from other works, he gives parallel texts in English, Latin, and where appropriate, Greek.

Among the other books recommended by Recorde, Euclid's *Phenomena* and a commentary on Proclus by Johannes Stöffler (1452-1531) top the list. The *Phenomena*, by the same Euclid (fl. ca. 295 B.C.E.) who wrote the famous *Elements*, applies

[55] Recorde, *Castle* (1556), 2 (three books named), 20 (Linacre's translation of Proclus specified), 98 (Cleomedes discussed).

geometrical demonstration to a series of astronomical theorems. Recorde proceeds to name several "Englyshe menne" whose works he admires: "Grostehed" (Robert Grosseteste, ca. 1168-1253, author of a *sphaera*), "Michell Scotte" (Michael Scot, d. ca. 1235, who wrote his own *sphaera*; a commentary on Sacrobosco is also ascribed to him and Recorde does not state which work is meant), "Batecombe" (possibly Roger Bacon, ca. 1219-1292), and "Baconthorpe" (Joannes Baco). However, according to the Master, their works and the works of other worthy authors remain in manuscript; the implied meaning is that they cannot be found as readily.

Recorde adds a warning about other authors whose books may be found in circulation:

> As for Plinye, Hyginius, Aratus, and a greate manye other, are to bee readde only of masters in such arte, that can iudge the chaffe from the corne, and Ptolemye that worthye writer and myracle in nature, is to harde for younge schollars, except they be fyrst instructed not onlye in the principles of the Sphere, but also well traded in Euclides his Geometrye, and also well exercised in the Theorykes of the Planetes.[56]

Melanchthon bragged about the place of Book 2 of Pliny's *Natural History* in the philosophical curriculum at Wittenberg; Recorde's slightly disparaging attitude is a surprising contrast. Hyginus and Aratus of Soli wrote astronomical poems describing the Greek constellations and the major circles of the celestial sphere. The unnamed "greate manye other," if they resemble Pliny and Aratus, are literary authors, not mathematicians, presenting mythology and entertaining descriptions under the guise of star lore. Ovid's *Metamorphoses* and Virgil's *Georgics* fall into this category, and both are quoted frequently by Melanchthon's classically-trained students.

Note that the traditional order of teaching is emphasized. After mastering *sphaera*

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[56] Recorde, *Castle* (1556), 99.

material, which is to be accomplished by reading several *sphaeras*, the student is to read Euclid's *Elements*, one or more unnamed *theoricas*, and finally the *Almagest*, all probably to be found in the London booksellers' stalls. Of course, Recorde's own textbooks have already been read to supply the elementary mathematics necessary to understand these books. Recorde's entirely appropriate admonishments concerning the proper order of teaching went unheard in some quarters. In the 1570s Henry Savile lectured on mathematics at Oxford, where formal classes in astronomy normally did not go beyond a *sphaera*. Savile, seeking to emulate the success of the German universities, declared his intent to follow what he understood to be their plan of teaching: bypassing the handbooks and going straight to the *Almagest*, the original source of astronomy. Naturally his undergraduate listeners found themselves woefully unprepared for the lectures, since the success of Wittenberg was founded precisely on what Savile disdained.[57]

Besides these explicit recommendations (and warnings), Recorde refers to many other authorities on astronomy and cosmography. In some cases he can have known of them only through secondary reports, as in the case of Parmenides' opinion on the uninhabitability of the arctic zones.[58] Another figure whom Recorde knew at second hand is C. Firmianus Lactantius (ca. 250 - ca. 325), an early Christian theologian who argued for a flat Earth on the basis of scripture. Copernicus makes a terse dismissal of Lactantius in *De revolutionibus* as the type of uninformed person whose criticisms need not be taken

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[57] Information about Savile's lectures comes from Robert Goulding, " 'How Can Alexandria Be Brought to Oxford?' Henry Savile's History of Mathematics and Institutional Reform," (paper presented at the annual meeting of the History of Science Society, Austin, Texas, 18-21 November 2004). For more on Savile and other mathematical lecturers at Oxford see Feingold, *Mathematicians' Apprenticeship*.

[58] Recorde, *Castle* (1556), 171.

seriously. The refutation of Lactantius in the *Castle of Knowledge* is too detailed, however, to have been inspired solely by Copernicus: the Church father appears as someone who not only endorsed a flat Earth, but rejected the antipodes (people living on the opposite side of the Earth) and accepted a flat heaven. Similar information appears in Stöffler's Proclus commentary, which we found on Recorde's reading list.[59] Nevertheless, he had access to a number of both classical and contemporary works, including the *Geographies* of Strabo (64/63 B.C.E. - ca. 25 C.E.) and Ptolemy; a *sphaera* by one Faber, not otherwise identified, who uses al-Farghānī's numbers for celestial measurements; and Reinhold's commentary on the *Almagest*, from which he takes two arguments for the sphericity of the element of water.[60]

But Recorde is most celebrated as an early reader of Copernicus; in fact, the *Castle* contains the first known reference to Copernicus in England. Because his most extended discussion ends on a positive note, with the Master cautioning the Student not to reject the Earth's motion out of hand, historians have sometimes taken the passage as an overt endorsement of heliocentrism. However, a careful reading shows that Recorde distinguished between different kinds of terrestrial motion.[61] According to the Master,

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[59] Recorde, *Castle* (1556), 103-104 (analysis of Lactantius). Compare *De rev*. (1543), fol. 4v (Lactantius only as flat-earther) and Stöffler, *In Procli Diadochi, authoris gravissimi, Sphaeram mundi, omnibus numeris longe absolutissimus commentarius* (Tübingen: Morhardinis, 1534), who discusses and refutes Lactantius at length.

[60] Recorde, *Castle* (1556), 171 (Strabo), 175 (Ptolemy's *Geography*), 154 (Faber), 138-41 (Reinhold). Reinhold's arguments appear in Ptolemy, *Mathematica constructionis*.

[61] The first modern observation of this distinction that I have found is John L. Russell, "The Copernican System in Great Britain," in *The Reception of Copernicus' Heliocentric Theory*, ed. Jerzy Dobrzycki (Dordrecht: D. Reidel, 1972), 190-191 Compare Johnson, *Astronomical Thought*, 126-28, where Recorde's full support for Copernicanism is extrapolated. Johnson, who quotes the key passage in full, is probably the main source for modern awareness of Recorde's "Copernicanism." Note that Westman does not include Recorde on his short list of early Copernicans in "Astronomer's Role," 136 n. 6, but places his on the list of people for whom the evidence is insufficient or inconclusive.

"circularre motion" of the Earth (rotation on its axis) cannot be refuted, "bycause those reasons doo not proceede so demonstrablye, but they may be answered fully." In contrast, "direct motion out of the centre of the world, seemeth more easy to be confuted." A full exposition of Copernicus is beyond the scope of an introductory work, but the Master promises someday to "so declare his supposition, that you shall not only wonder to hear it, but also peraduenture be as earnest then to credite it, as you are now to condemne it."[62] Recorde's concluding statement has been interpreted as a sign that he regarded heliocentrism as an accurate physical description of the world, but put off discussion of the matter for a more advanced work. However, his promise is also compatible with an awareness of the difficulties faced by an Earth-bound observer seeking to know the true arrangement of the heavens.

Since Recorde never wrote his *theorica*, we cannot be sure whether he was a Copernican or believed something like the Wittenberg Interpretation. He may have preferred a cosmology like Calcagnini's with a rotating central Earth, which would produce astronomical phenomena conceptually indistinguishable from the usual Ptolemaic cosmology. His affirmation that the Earth's centrality is more difficult to disprove than its immobility points to a hierarchy of knowledge in which mathematics provides the greatest certainty. Elsewhere he wrote that "It is confessed emongeste all men, that knowe what learnyng meaneth, that besides the Mathematicalle artes, there is noe vnfallible knoweledge, excepte it bee borowed of them."[63] No argument or demonstration can be irrefutable without a mathematical basis.

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[62] Recorde, *Castle* (1556), 164-65.

[63] Recorde, *The whetstone of witte, which is the seconde parte of Arithmeticke* (London: Jhon Kyngstone, 1557), fol. b1v.

Applying Recorde's principle to the arguments he might have marshaled against both kinds of motion of the Earth, we can see why he would regard only one as reliable. Common arguments against the rotation of the Earth drawn from the *Almagest* and Aristotelian natural philosophy are purely physical: earth is too heavy an element to move so quickly; its natural motion is linear; clouds, birds, and projectiles would be left behind as it rotated. Arguments for its centrality, on the other hand, include both physical and mathematical approaches: the conclusions that the horizon would not divide the zodiac into two equal arcs and that there would be no equinox, for example, result from mathematical reasoning. As most of Recorde's educated contemporaries would have agreed, mathematics provides a more certain basis for knowledge than physics, whether or not they would regard that knowledge as better in some fashion. It may be for this reason that he added arguments for the Earth's centrality to the *Castle* but set aside arguments for the Earth's immobility.[64]

A second reference to Copernicus in the context of Recorde's star catalogue confirms that he had access to *De revolutionibus* and did not base his description on hearsay. The last section of the *Castle* includes an enumeration of the constellations and the stars they contain. Describing the constellation Chiron (modern Centaurus), he writes that Ptolemy assigned four stars to the spear, but that an old translation of the *Almagest* mislabeled the group of four as the shield ("Clypeus is translated for Hasta"). Various authors, misled by the translation, have erroneously appropriated other stars for the spear;

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[64] Recorde, *Castle* (1556), 157-64. Ostensibly, the Master does not rehearse arguments for immobility because it is "follye" to prove what everyone accepts. But why should this line of reasoning not apply equally to centrality, which everyone accepted?

he identifies Stöffler, Schöner, Copernicus, and Reinhold among this group.[65]

[65] Recorde, *Castle* (1556), 270. Compare *Almagest* 8:1, p. 394 ("4 stars in the thyrsus,") and *De rev*. (1543), Book 2, fol. 61r (four stars "in scuto," i.e., in the shield).

Early Exploration in the North Atlantic

To understand how the disparate threads of navigation and the first printed astronomical works in English converge in the figure of Recorde, we must return to the matter of European ocean voyages before the introduction of nautical astronomy to northern Europe. As I mentioned at the beginning of this chapter, the islands of the north Atlantic attracted inhabitants of its coasts out to the deep ocean much earlier than the Canaries drew the attention of the Portuguese, with the result that medieval Scandinavians populated Iceland, Greenland, even North America (if only for a short time). New lands were typically sighted when a ship was blown off course, but the discoverers could find their way back on later voyages; later generations could sail to Iceland and Greenland with enough confidence to make regular trade and colonization feasible.

Little evidence survives to tell us how the Scandinavians steered a course, but it appears that they used dead-reckoning and the other techniques of pilotage: experience, instruction, and the observation of environmental cues including currents, the presence of ice, and the behavior of birds. They also, sometimes, followed a method of latitude sailing; how they may have found latitude is obscure but involved comparing the elevation of Sun or polestar with elevation at a known port. Probably they neither achieved nor cared about achieving a level of accuracy comparable to the level to which pilots using the "Regiment of the Sun" aspired. Early in the fifteenth century English ships sailing out of Bristol were visiting Iceland to trade with colonists there and to take advantage of the bountiful fisheries nearby. English ships may have visited Greenland as well or learned of its existence from Icelanders. In the 1480s Bristol merchants began backing westward expeditions in search of the fabled Isle of Brasil and untapped fisheries.[66]

The expeditions throughout the fifteenth century gained for the English invaluable experience in shipbuilding and seamanship using rutters, dead reckoning, and the other techniques of pilotage, facilitating regular visits to Iceland but not routine transoceanic trips. The situation began to change with the arrival of a Venetian navigator who knew something of astronomical navigation. Zuan Caboto, better known to Anglophone scholars as John Cabot (ca. 1451-1498), received a patent from Henry VII in 1496 to set out from Bristol in search of Brasil and Cipango (Japan). His first voyage was unsuccessful, but a second one in 1497 made landfall somewhere on the northeastern seaboard of North America, which he believed to be Cathay. His ship disappeared at sea on his third English voyage the following year.[67]

John Cabot was survived by a son, Sebastian (ca. 1481/2-1557), who had accompanied his father on the 1497 voyage and had learned something of navigation from his father. Sebastian entered the service of the English king as mapmaker and headed an expedition to Labrador in 1508. When Henry VIII proved to be less interested in exploration than his father had been, Sebastian left for greener pastures working for Spain. In 1518 he became the *piloto mayor* of the *Casa de la Contratación* (House of

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[66] Marcus, *Conquest of the North Atlantic*, discusses the evidence for medieval exploration and nautical technology of the Irish, the English, and especially the Norse. David Beers Quinn, *England and the Discovery of America, 1481-1620* (New York: Alfred A. Knopf, 1974), 3-87, gives a somewhat unskeptical assessment of evidence for westward English voyages in the period up to the early 1490s.

[67] I have used C. Raymond Beazley, *John and Sebastian Cabot: The Discovery of North America* (London: T. Fisher Unwin, 1898) as a guide to the Cabots despite its age; Beazley quotes from many primary sources extensively or even in full (for John Cabot see pp. 33-111). The discovery of a contemporary account of the voyage in the mid-twentieth century greatly increased modern knowledge of John Cabot. For a recent historiography see Peter E. Pope, *The Many Landfalls of John Cabot* (Toronto: University of Toronto Press, 1997), who argues that John Cabot must have used latitude sailing; his basic account of John Cabot's voyages is on pp. 13-42.

Trade) at Seville. As *piloto mayor*, he instructed and licensed pilots, certified navigational instruments, and maintained an evolving world map which provided the basis for all official charts. Several times he considered returning to England, but negotiations fell through until 1547, after the death of Henry VIII. He departed Seville for England the next year, bringing with him invaluable knowledge of cartography and navigation, as well as familiarity with the administration of institutions devoted to sailing and exploration.[68]

A group of Londoners jointly financed an expedition to find a northeast passage to Cathay in 1553. Sebastian Cabot was the governor of the semi-formal group. Hugh Willoughby was named captain general of the expedition, and Richard Chancellor (d. 1556), an experienced navigator, was named pilot general. Three ships set out, but one became separated in a storm from the other two, which lost their entire crews after a disastrous decision to overwinter in the far north. The third ship, carrying Chancellor, safely reached the White Sea. Chancellor traveled overland to Moscow, negotiated a trade agreement with Tsar Ivan IV (the Terrible), and returned to England. On February 26, 1555, Queen Mary and her husband Philip chartered the Muscovy Company, which was to have exclusive trading rights with Russia.[69]

Robert Recorde saw the potential of the new trading company and began advertising himself as an expert in the art of navigation. In the *Castle of Knowledge* he

[68] For Sebastian Cabot's initial employment by England and his time in Spain, see Beazley, *John and Sebastian Cabot*, 112-160; and Pope, *John Cabot*, 48-59. On the House of Trade see also Goodman, *Power and Penury*, 74-76.

[69] T. S. Willan, *The Early History of the Russia Company, 1553-1603* (Manchester: Manchester University Press, 1956) is a standard account of the Muscovy Company; see especially chapter 1, "The Establishment of the Company," 1-18; for Cabot's employment in England and his involvement in the Company see Beazley, *John and Sebastian Cabot*, 176-206.

hinted at his familiarity with geography and with recent discoveries: the Cape of Good Hope lies on the same meridian as Venice; Guinea, which has been visited by the English, lies past the Tropic of Cancer near the equinoctial, as does Calecut (Calcutta); lunar eclipses occur at different local times in London and Calecut; mariners have measured the sea-floor at only a hundred fathoms, or about a tenth of an English mile.[70] He dedicated *The Whetstone of Witte*, his final book, to “the right worshipfull, the gouerners, Consulles, and the reste of the companie of venturers into Moscouia.” In the dedication he promised that, if they liked the *Whetstone*, he would “for your pleasure, to your comforte, and for your commoditie, shortly set forthe soche a booke of Nauigation, as I dare saie, shall partly satisfie and contente, not only your expectation, but also the desire of a greate nomber beside.” His projected book would include a history of the recent “Northlie Nauigations.”[71]

Recorde did not live long enough to write his navigational treatise or become deeply involved with the Muscovy Company. However, his series of publications made the English dream of mathematical education for tradesmen and gentlemen a reality. Generations learned arithmetic from the *Ground of Artes*; the *Castle of Knowledge*, which went through a second edition, played its own smaller part in bringing astronomy to an English-only readership. Potentially at least, its readers also became aware of prominent Lutheran mathematicians and their sensible method of pedagogy, though we have seen one case where his prescriptions were ignored by an over-ambitious professor. In the next chapter we shall encounter a series of Tudor mathematicians and other writers

[70] Recorde, *Castle* (1556), 85-87, 118-19, 142, 184. The Cape of Good Hope is actually several degrees east of Venice.

[71] Recorde, *Whetstone of witte*, fol. a2r (dedication), a3r-v (projected navigational book).

on astronomy and navigation. Several of them were active in the 1550s, overlapping Recorde's period of activity, but their cumulative impact became most apparent in the 1570s.

CHAPTER SEVEN

ASTRONOMY AND NAVIGATION IN ELIZABETHAN ENGLAND

The previous chapter framed the interval from the 1480s to the 1550s as a time of maturation for English mathematics. Caxton's translation and publication of the *Myrrour of the worlde* in 1481 is regarded as a watershed in the history of English astronomy--the first publication of an astronomical text by an English printer--but the book itself is a minor work directed at a popular audience. In contrast, the continent had already seen a specialized scientific printing press in Regiomontanus' short-lived venture and important astronomical textbooks including Sacrobosco's *Sphaera*, the *Theorica planetarum*, and Peurbach's *Theoricae novae* had gone through multiple editions. In 1556, manuscripts and Latin publications from across the Channel still provided the bulk of astronomical works, but the English had begun to establish a foundation for study in their own nation. Recorde stands at the end of this process by virtue of having written a systematic course of study in mathematics, working from simple arithmetic and geometry to advanced applied mathematics, in imitation of the highly successful model in use at universities in Germany and elsewhere.

In this chapter we look at the continued promotion of astronomy and navigation in England beginning in the 1550s. In this phase, mathematicians had the luxury of assuming the availability of the most elementary textbooks in arithmetic and geometry. It should be noted, however, that the *sphaera* and other astronomical textbooks do not fall into this class. Unlike the *Ground of Artes*, which was in print almost constantly for the remainder of the sixteenth century, Recorde's *Castle of Knowledge* only went through two editions, with the result that alternate English *sphaeras* appeared to satisfy the demand for basic astronomy.

The first two sections overlap with the career of Robert Recorde. I begin with an early Copernican ephemeris by an otherwise obscure mathematician, John Feild, that has achieved enhanced notoriety because it includes a preface by the fabled Elizabethan scholar and "Queen's conjuror" John Dee. There follows a section on the mathematician and astronomer Thomas Digges. My account focuses on the two works that have earned for Digges a place among the short list of true Copernicans in the sixteenth century: a study of the nova of 1572, which he hoped would enable astronomers to determine which of the two world-systems was physically true; and a translation of a short passage from *De revolutionibus*. Next I take up the subject of literature on navigation in Elizabethan England, including contributions by Digges and Dee. I conclude with two authors compiling continental astronomical works and translating them into English, both drawing heavily from Lutheran mathematicians discussed in chapter five. One is a *sphaera* sometimes cited in modern studies as a typical example of the English reaction to Copernicus; I identify its origin for the first time and suggest why it has not been identified previously. The other is a collection of the first English *theoricas*, also translated but this time openly, in large part from Lutheran sources.

The Feild-Dee Ephemeris (1556)

In the year of the publication of Recorde's *Castle* there appeared another English work with a favorable attitude towards Copernican astronomy: an ephemeris prepared by a minor astrologer, John Feild (ca. 1520-1587).[1] Feild calculated a set of astronomical predictions for the year 1557 on the meridian of London, based on Reinhold's *Prutenic Tables*.[2] Prefixed to it was a letter to the reader by John Dee (1527-1608/9), Feild's associate and possibly his teacher. Dee had studied at Cambridge in the 1540s and been granted the B.A. and M.A.; he had also visited the Netherlands, returning with instruments from Gemma Frisius and Gerard Mercator, studied at Louvain, and lectured on Euclid's *Elements* at Paris. In 1555, both Feild and Dee were among a group arrested on suspicion of witchcraft, probably based on their having calculated the queen's horoscopes. For Feild, the publication of an ephemeris the following year was a high point, but Dee had just begun his climb to fame as one of Tudor England's most erudite yet controversial scholars.[3]

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[1] For the little that is known about Feild's life, see *DNB* 19:237-38.

[2] John Feild, *Ephemeris anni .1557. currentis iuxta Copernici et Reinhaldi canones ... supputata ... Adiecta est etiam brevis quaedam Epistola IOANNIS DEE...* (London: Thomas Marshe, 1556).

[3] The secondary literature on John Dee is enormous, and his own body of work is not insubstantial, especially if the "angel diaries" and other works rediscovered in manuscript are included. Dee included a list of forty-eight published, unpublished, and incomplete "Bookes and Treatises," some now lost, in *A Letter, Containing a most briefe Discourse Apologeticall* (London: Peter Short, 1599), fol. A3v-B1v, that suggests the breadth of his work, covering history, sundry mathematical arts, religion, and alchemy. Among modern studies, several works stand out as turning-points in Dee studies. The standard biography is still Charlotte Fell-Smith, *John Dee (1527-1608)* (London: Constable, 1909), an early attempt to treat Dee as a serious figure rather than a fool or a charlatan. Taylor, *Tudor Geography: 1485-1583* (London: Methuen, 1930), and *The Mathematical Practitioners of Tudor and Stuart England* (Cambridge: For the Institute of Navigation at the University Press, 1954; reprint, Cambridge: Cambridge University Press, 1967); and Johnson, *Astronomical Thought*, approached him as a serious mathematician, but only by divorcing his work in mathematics, navigation, and geography from his "magical" studies. Conversely, Yates, *Theatre of the World* (Chicago: University of Chicago Press, 1969); and Paul French, *John Dee: The World of an Elizabethan Magus* (New York: Routledge and Kegan Paul, 1972), stressed his occult studies at the expense of his mathematical ones. Among the many studies that have appeared since Yates' early works, three monographs deserve special attention as attempts to understand Dee as a composite figure: Nicholas

Among the astronomical books published in England, the Feild ephemeris of 1556 remained for almost two decades the only work to adopt Copernican astronomy at a technical level.[4] The letters to the reader in which Feild and Dee declare their support for the calculational superiority of Copernican astronomy have garnered a little attention from historians seeking to ascertain early English reactions to heliocentrism. Dee's preface articulates the normal sixteenth-century reaction of admiration for critical errors corrected by Copernicus combined with silence about the new cosmology. After opening with general remarks about the inaccuracies of the old tables, he raises the subject of the new astronomical theories:

> I have also been hoping that others, especially those who treat and labor over things concerning Astronomy both many and great, have at last learned something by hearsay about the writings of COPERNICUS, or of Reinhold and Rheticus, or failing that, at least their names; and that the ears of those men have already resounded longer with their remarkable fame.[5]

Their remarkable achievements include more accurate predictions of the fixed stars; a correction of the Mercury model, which is said to be as much as thirteen degrees in error; and adjustments to the models of the other planets and the length of the tropical year--all unsurprising and easily reconcilable with geocentrism.

The letters of Feild present the informed with some ambiguity. A prefatory letter

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H. Clulee, *John Dee's Natural Philosophy: Between Science and Religion* (New York: Routledge, 1988); William H. Sherman, *John Dee: The Politics of Reading and Writing in the Renaissance* (Amherst and Boston: University of Massachusetts Press, 1995); and Deborah E. Harkness, *John Dee's Conversations with Angels: Cabala, Alchemy, and the End of Nature* (Cambridge: Cambridge University Press, 1999).

[4] In the list of early English astronomical works included as an appendix to Johnson, *Astronomical Thought*, the first technical "Copernican" work after 1556 is Digges' treatise on the nova, published in 1573.

[5] "Sperabam etiam alios, illos praesertim qui in Astronomicis tum multa, tum magna tractant, & moliuntur, de COPERNICI, aut Rhetici & Reinhaldti scriptis, vel eorum saltem nominibus, auditione tandem aliquid accepisse: praeclaramque horum famam, istorum hominum aures iam circumsonasse diutius." Dee, in Feild, *Ephemeris anni 1557*, fol. A1r (my translation).

expresses sentiments similar to those of Dee: other ephemerides following the hypotheses of the Alfonsine Tables are full of errors, but his own ephemerides "follow the authors N. Copernicus and Erasmus Reinhold, whose writings are established and founded with true, certain, and sound demonstrations."[6] A second letter to the reader placed at the end of the book begins with a cryptic warning:

> I want to warn you, reader, that I have written my Ascents and descents of the planets in little tables in another way than the mass of Astronomers up to this point have written [them], not so that I might criticize them in it, but because I might present for them the principle of a certain more informed and perfected Astronomy, which will demonstrate most secret mysteries of nature to be drawn from those labors of the planets around their epicycles, as you will understand others (so I hope) from it [being] more spread out and plain.[7]

The vague praises in the remainder of the two authorial letters shed no further light on Feild's opinion of the Copernican cosmology; modern assessments range from viewing him as uncontroversially heliocentrist to striking him even from the list of also-rans.[8] Certainly he has been deliberately obscure in speaking of the "most secret mysteries." In revealing that an astronomical principle is to be demonstrated from the epicycles, however, it is possible that he meant the mathematical initiate to understand the truth of the Copernican system: the epicycles of Ptolemaic astronomy represent the great orb of the Earth's annual revolution.

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[6] "Quapropter hanc tibi peruulgaui Ephemeridem Anni .1557. in ea authores sequuntus N. Copernicum et Erasmum Reinholdum, quorum scripta stabilita sunt et fundata veris, certis, & sinceris demonstrationibus." Feild, *Ephemeris anni 1557*, fol. A3r (my translation).

[7] "Monere te volui, lector, aliter in tabellis meis Ascensus me & descensus planetarum descripsisse, quam vulgus Astronomorum nactenus descripserit, non quod illos in eo reprehendam, sed quod eruditioris cuiusdam et perfectioris Astronomi, judicium illis praetulerim, qui ex istis planetarum circa suos epicyclos laboribus secretissima natura mysteria elicienda demonstrabit, vti ab eodem (vt spero) fusius alias planiusque intelliges." Feild, *Ephemeris anni 1557*, fol. E4r.

[8] John Russell, "Copernican System in Britain," 192, accepts Feild as a heliocentrist; in contrast, Westman, "Astronomer's Role," 136 n. 6, does not count him in the list of candidates for whom there is not adequate information. *DNB* 19:238 notes that there is inadequate material to make a determination, but regards him as unlikely to have been a heliocentrist.

Feild's ephemeris holds significance beyond providing a list of potential supporters for the new astronomy. It also shows us that at an early stage, English mathematicians considered the names of Lutheran astronomers to be closely intertwined with that of Copernicus. By producing the *Prutenic Tables*, Reinhold had maximized accessibility to the predictive power of *De revolutionibus*, so of course both Dee and Feild mention him in the same breath as Copernicus. Dee's enthusiasm points to something more: he believes that astronomers should have heard at least some rumor of Copernicus, Reinhold, or *Rheticus*, who in 1550 published his own ephemeris based on *De revolutionibus*. We see a similar phenomenon in a later generation: Richard Forster, after praising Dee for the rebirth of mathematics among the English, worried that unless a successor were soon found, "the whole might collapse with the heavens of Copernicus and Reinhold."[9] Feild prepared a second ephemeris for following years lacking the confrontational addresses to the reader, but it was his last publication, and after him no more English mathematicians brought out ephemerides based on the Prutenic Tables. Perhaps they utilized the Copernican ephemerides of Johannes Stadius, which were available through the end of the century.[10]

[9] ". . . tota cum Copernici & Reinholdi coelo corruat." Richard Forster, *Ephemerides meteorographicae ad annum 1575* (London: J. Kingston, 1575).

[10] Gingerich, "Reinhold and Dissemination of Copernican Theory," in *Eye of Heaven*, 231.

Thomas Digges (ca. 1546-1595)

One of the leading mathematicians of Elizabethan England, Thomas Digges was the son of another and the intellectual child of a third. Leonard Digges (ca. 1515 - ca. 1559) wrote extensively on theoretical and applied mathematics.[11] Although he produced several books for publication, only two of his surviving works saw print in his lifetime. One was *Tectonicon* (1556), a handbook on surveying, masonry, carpentry, and affiliated crafts, which went through about twenty editions in the sixteenth and seventeenth centuries. The other was *A prognostication of right good effect*, Digges' contribution to the flourishing market in almanacs.[12] The first surviving edition is from 1555, though remarks by the author suggest it was already a revised edition; editions from 1556 and later bear the title *Prognostication everlasting*. Intended for consultation year after year, Digges' perpetual almanac contained information standard to almanacs: calendars, tide tables, astrological meteorology and medicine, and so forth. Later editions added diagrams showing the sizes of the planets compared to Earth in an attempt to refute skeptics, who he reports had been astonished at his statement that the Sun would contain the Moon 7,000 times.[13]

From the beginning, the *Prognostication* included an address "Agaynst the reprouers of astronomie, and sciences Mathematicall" revealing that Leonard Digges was familiar with and approved of the Lutheran providential approach to the heavens. As part

[11] For basic biographical information on the Diggeses, see *DNB* 16:169-173; and *DSB* 4:97-98.

[12] The widespread appeal of the almanac genre in Tudor England and later is discussed in Bernard Capp, *English Almanacs 1500-1800: Astrology and the Popular Press*, (Ithaca: Cornell University Press, 1979). Leonard Digges may also have prepared yearly almanacs, since fragments of one survive (*DNB* 16:169); since they were subjected to heavy use and then disposed of, entire editions of almanacs may be lost.

[13] Leonard Digges, *A prognostication euerlasting of ryght good effecte*... (London: T. Gemini, 1556), fol. 4r-v. The Ptolemaic value for the ratio of solar to lunar volumes is 6644 1/2 to 1; *Almagest*, 5.16, p. 257.

of his defense of astronomy, he recommends that “all nyce diuines, or (as *Melancthon* termeth them) *Epicurei Theologi*” read Melanchthon’s demonstrations of scriptural support for astronomy in his letters to Grynaeus and Schöner and peroration to Cardanus. Brief quotations confirm that Digges hoped to refute the “nyce diuines” with help from the preface to Grynaeus in Sacrobosco’s *Sphaera*.[14]

Leonard Digges died while his son was still young, and John Dee saw to the boy’s mathematical education.[15] As an adult, Thomas took up the task of publishing his father’s mathematical manuscripts with additions of his own work. The joint posthumous publications of the Diggeses include the *Pantometria* (1571, 1591), a treatise on geometry and surveying by Leonard with a supplementary *Mathematicall Discourse of Geometricall Solids* by Thomas; the *Stratioticos* (1579, 1590), combining an arithmetic textbook by Leonard with an algebra textbook and a discourse on military organization by Thomas; and a new edition of the *Prognostication* with new tracts by Thomas that will be discussed shortly. Late in his life, Thomas brought out new editions of the *Pantometria* and the *Stratioticos* with new material on gunnery.

In November 1572 a new star appearing in the constellation Cassiopeia astonished the astronomical community of Europe. Although change in the heavens contradicted Aristotelian doctrine, the new object was indisputably celestial: it was unusually bright but otherwise starlike, and astronomers attempting to measure its parallax concluded that

[14] Leonard Digges, *A prognostication of right good effect fructfully augmented...* (London: Thomas Gemini, 1555), fol. *4r. Phrases quoted from the Grynaeus preface include *Epicurei Theologi*; *manifestum insaniae genus*; *quod magis opus habent medicis, quam Geometris*; and *Sinamus vna cum Epicuro ineptire*. Compare *CR* 2:533. I have not yet identified the source(s) of other quotations.

[15] For instance, Dee, *Parallaticae Commentationis Praxeosque Nucleus quidam* (London: John Day, 1573), fol. A2v, speaks of Digges “my fittest heir” (*meus dignissimus haeres*); while Digges in a preface to Dee’s book, fol. A2r, calls Dee “my dearest friend and second Mathematical Father” (*charissimo meo amico & Parente altero Mathematico*).

it must lie beyond the Moon. Dee contributed a minor work, the *Parallaticae Commentationis Praxeosque Nucleus quidam* (1573), to the flurry of publications precipitated by the nova. His mathematical son Digges declared an interest in the Copernican system with a substantial treatise on the new star, the *Alae seu scalae mathematicae* (1573). The *alae* of the title are the wings of the soul described in Plato's *Phaedrus* and identified by Melanchthon as arithmetic and geometry, which enable the mind to understand astronomy.[16] The *scalae* is a staircase or ladder, perhaps a reference to Jacob's ladder on which angels moved between heaven and Earth (Gen. 28:12).

Digges presents his treatise as another sort of ladder supporting an intellectual ascent to the heavens, where the reader will contemplate the true nature of the celestial realm. Since the journey cannot be made in the body, it must begin with the eyes, according to the Platonic dictum that "Men are given eyes for the sake of astronomy."

> Nor would things so varied, and placed so far away, have been sought out or examined by the eye of human intellect unless God had both excited and advanced the studies of certain of the greatest men. And it is not possible for the human soul not to conclude that there is a God, who governs by such a wonderful activity. For, indeed, nothing of such kind of occurrence can either exist or continue by another power without a mind. Therefore, since the meticulous and assiduous contemplation of the Celestial Machine most vehemently excites or confirms the belief in God in the souls of men, we ought to acknowledge that Plato rightly said not only wisely but also religiously that *Men are given eyes for the sake of astronomy*. They are given to men (even the Faithless and Pagans) chiefly for this cause: that they might be guides to seeking some notice of God. . . . Consequently, among Philosophers only those who spurned Astronomy were professed *atheoi*, and having removed providence they also removed the immortality of our souls. Wherefrom, if they had arrived at this doctrine, they would have detected the manifest traces of God in nature, by perceptions of which they would have been brought to acknowledge that this universe is formed and governed by some mind.[17]

[16] Melanchthon, *Orations*, p. 93.

[17] "Neque res tam varie adeoque procul posite, aut inquisitae essent, aut humani ingenij acie perspecte, nisi Deus studia quorundam summorum virorum et excitasset, et prouexisset. Neque fieri potest quin statuat humanus animus Deum esse, qui tam mirando opificio moderetur. Nil etenim tale casu, aut alia vi vlla sine mente existere aut constare potest. Cum igitur exquisita assiduaque Machine Coelestis contemplatio

Digges found his religious motivation for the study of the heavens in Melanchthon's preface to Sacrobosco's *Sphaera*, which first laid out the providentially-based interpretation of astronomy. In fact, the passage is composed almost entirely of quotations from Melanchthon, rearranged and slightly altered. Compare Digges above with the extracts from Melanchthon below.

> For such varied things, which are placed so far away, would not have been investigated or perceived by human sight had God not roused and advanced the studies of some outstanding men. . . . Plato very plainly says that men were given eyes for the sake of astronomy. . . . For it is not possible for the human mind not to conclude that there is a mind that rules and governs everything, if it contemplated these established courses and laws of the great circuits and stars. For no such thing can exist or continue by chance or by another power without a mind. For this reason--if astronomy corroborates the belief about God in the minds of men--we have to consider that Plato said not only learnedly, but also piously that eyes are given to us because of astronomy. For they are certainly given to us chiefly for the reason that they may be our guides for searching for some knowledge of God. Furthermore, only those among the philosophers who spurned astronomy were professedly ungodly [*atheoi*]; having done away with providence, they also removed the immortality of our souls. If they had reached this knowledge, they would have perceived the manifest traces of God in nature, and, having noticed them, they would have been forced to acknowledge that the universe is made and governed by a mind.[18]

Thomas Digges may have been drawn to the preface by his father's recommendation in the *Prognostication*. The son fully embraced Melanchthon's arguments and made them his own, including the special place of Epicureanism. Elsewhere Digges compares the Epicureans to dogs slashing at the mathematical arts with their teeth. Possibly he even

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vehementissime aut excitet aut confirmet in hominum animis de Deo opinionem, non sapienter solummodo sed religiouse etiam Platonem dixisse iure confiteri debemque, *Astronomiae causa oculos hominibus esse datos*: sunt enim praecipue ob hanc causam hominibus dati, vt ad querendam aliquam de Deo noticiam (Infidis etiam et Ethnicis) duces essent. . . . Proinde inter Philosophos soli illi qui Astronomiam aspernati sunt, ex professo fuerunt *atheoi*, et sublata prouidentia etiam immortalitatem animatum nostrarum sustulerunt, qui si attigissent hand doctrinam, manifesta dei vestigia in natura dprehendissent, quibus animaduersis coacti essent fateri mente aliqua hanc rerum vniuersitatem conditam esse et gubernari." Thomas Digges, *Alae seu scalae mathematicae, quibus visibilium remotissima Coelorum Theatra conscendi, & Planetarum omnium itinera nouis & inauditis Methodis explorari*... (London: Thomas Marsh, 1573), fol. A1v.

memorized the preface, quoting it from memory, as he is reported to have memorized the astronomical section of Palingenius' *Zodiacus Vitae*, a cosmographical poem popular in the Tudor period.[19]

Digges expresses a preference for the Copernican system in the *Alae* together with his hopes that it will be confirmed by further observation of the nova. The treatise begins with a description of the location of the new star in relation to the ancient stars of the constellation Cassiopeia using coordinates from Copernicus' star catalogue, "with the typographical errors corrected."[20] In the preface, shortly after introducing the concept of reading the heavens providentially, Digges turns to the subject of Copernicus.[21] The ancients, he writes, began with *Theoricas* and proceeded to look for parallaxes and distances where they ought to have begun with parallaxes, which can be observed, and proceed to theories; this sound procedure would have revealed whether the daily rotation ought to be assigned to the heavens or the Earth. Even the Earth's central place might have been challenged, since nobody has been able to demonstrate what has remained received opinion.

> Nevertheless, they are forced to acknowledge that the Earth is not the center of the solar Orb. It is even necessary to concede the same thing in the remaining wanderers, since not only are they carried around with unequal motions (in their Orbs), but they even seem to appear sometimes greater, sometimes lesser, which could not even happen if they went around in their Orbs uniformly and equally

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[18] Melanchthon, *Orations*, 106-107 (translation Salazar's); for the Latin see *CR* 2:531.

[19] The Epicurean "dogs" appear in Digges, *Alae*, fol Aiiijr. For the report that Digges quoted Palingenius from memory, see Gabriel Harvey, *Gabriel Harvey's Marginalia*, ed. G. C. Moore Smith (Stratford-Upon-Avon: Shakespeare Head Press, 1913), 161.

[20] ". . . à Copernico traduntur (Typographis erroribus emendatis)," Digges, *Alae*, fol. Aijr; *De rev*. (1543), fol. 49r.

[21] The following discussion summarizes Digges, *Alae*, fol. A2v-A3v. Portions are translation in Johnson, *Astronomical Thought*, 158-59.

> from the center of the remote Earth. . . .[22]

To preserve their *Theoricas*, geocentrists abandoned homocentric orbs in favor of eccentrics and epicycles, which moved nonuniformly around their centers (a reference to equants), until they exchanged a symmetrical anatomy of the world for a monster grafted from human parts, an image from the letter to the Pope in *De revolutionibus*.

Copernicus (Digges continues) proposed new hypotheses based on the Earth's motion. The nova had decreased in brightness since its appearance in November. Digges attributes the change to the Earth's motion around the Sun carrying us away from the star. Writing in February, he predicts that the nova will continue to diminish until the spring equinox, then grow larger and brighter as we approach it again until, around the autumnal equinox, it will again have grown to notable size. Varying distance is the only cause of the star's varying brightness, since physical principles prevent any change in its true brightness. (No explanation is offered why physical principles permitted the star to be generated in the first place.) Mathematics, not physics, is the key:

> Therefore, since I am undertaking something that is perceived to be necessary, then Mathematics has rules for measuring the situation, distance, and size of this stupendous star, and for manifesting God's marvelous work to the entire race of mortals (who aspire to understand something Celestial, and not lie totally buried in earth), and for considering Theoricas, and deciding the true Syntaxis of the World, and measuring most exactly the Parallaxes of Celestial Phenomena.[23]

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[22] ". . .tamen confiteri coguntur, Terram non esse Orbis solaris centrum, idem etiam in reliquis erraticis concedere necesse est, cum non solum inequalibus (in suis Orbibus) motibus circumferri, sed etiam nonnunquam maiores nonunquam minores apparere videantur, quod quidem contingere non potuisset, si in suis Orbibus vniformiter et aequaliter a centro terrae remotae circumagerentur. . . ." Digges, *Alae*, fol. A2v (my translation).

[23] "Cum igitur rem adeo necesariam esse animaduerti, tum ad huius stupendi syderis situm, distantiam, magnitudinem metiendas, Deique mirandum opus vniverso mortalium generi (qui aliquid Coeleste sapere affectant, et non omnino tellure sepulti iacent) manifestandum, tum ad Theoricas examinandas, et veram mundi Syntaxin constitudendam, exactissime Coelestium Phoenomenoon Parallaxeis mesurandi, Mathematica habere praecepta." Digges, *Alae*, fol. A3v (translation based partly on Johnson, *Astronomical Thought*, 159).

The hope of Digges to vindicate heliocentrism was disappointed as the star continued to fade into invisibility.

Three years later Thomas Digges provided public confirmation of his own adherence to Copernicanism in a supplement to a new edition of his father's perpetual almanac. Between 1573 and 1603, at least seven editions of the *Prognostication everlasting* were printed with three new sections prepared by the son: first, "A perfit description of the Caelestiall Orbes according to the most aunciente doctrine of the Pythagoreans, Latelye reuiued by Copernicus and by Geometricall Demonstrations approued"; second, "A short Discourse touchinge the Variation of the compasse"; and third, "Errors in the Arte of Nauigation commonly practized."[24] The "Perfit description" is actually a loose translation of several chapters from the first book of *De revolutionibus*, with an important early diagram of the Copernican cosmology. The material translated includes Copernicus' own explanation of the heliocentric arrangement and distances of the planets (chapter 10 of *De revolutionibus*), arguments against the Earth's motion (chapter 7), and their refutation by Copernicus (chapters 8 and part of 9). A passage added in translation compares the small size of the Great Orb of the Earth to "that fixed Orbe garnished with lightes innumerable and reachinge vp in *Sphaericall altitude* without ende."[25] Only the daily motion of the heavens had imposed a limit on the size of the sphere of fixed stars; if they were motionless, the stars might extend infinitely outwards. Copernicus acknowledged the possibility; Digges accepted it as fact.

[24] Leonard Digges, *A prognostication euerlastinge of right Good effecte fruitfully augmented by the auctour ... Published by Leonard Digges Gentleman. Lately corrected and augmented by Thomas Digges his son* (London: Thomas Marsh, 1576), fol. M1r-P2r. The first full description and analysis of the "Perfit description," including a transcription, is Johnson and Larkey, "Thomas Digges, the Copernican System, and the Idea of the Infinity of the Universe in 1576," *Huntington Library Bulletin* 5 (1934): 69-117.

[25] Thomas Digges, "Perfit description," in Leonard Digges, *Prognostication* (1576), fol. N4r.

Unfortunately for the historian, the letter to the reader praises Copernicus enthusiastically but vaguely. Digges' commitment to the superiority of heliocentrism, however, cannot be in doubt.

> There is no doubte but of a true grounde truer effects may be produced then of principles that are false, and of true principles falshod or absurditie cannot be infered. If therefore the Earth be situate immoueable in the Center of the worlde, why finde we not Theorickes vppon that grounde to produce effects as true and certaine as these of *Copernicus*? VVhy cast we not away those *Circulos Aequantes* and motions irregulare, seing our owne Philosopher *Aristotle* him selfe the light of our Vniuersities hath taught vs: *Simplicis corporis simplicem oportet esse motum*.[26]

A conservative Wittenberg astronomer such as Peucer might have responded at this point that Digges intended to throw the baby out with the bathwater, since the equant (the only aspect of the old astronomy specified) could be cast aside while retaining geocentrism. Only a hint surfaces in the preface that Copernicus offered advantages beyond the restoration of uniform circular motion: the followers of Ptolemy "haue bin forced to admit" to their astronomy "the continuall errors that from time to time more & more haue bin discouered, besides the infinite absurdities in their Theorickes."[27]

Digges intended a two-stage campaign for the promotion of Copernicanism in England. The publication of the "Perfit description" completed the first stage by making available an English-language defense of the Earth's motion on natural philosophical grounds. The chapters in which Copernicus attempted to respond to philosophically-based criticism refuted the belief that he intended *De revolutionibus* as a mathematical fiction. At the same time, "familiar, naturall reasons" drawn from philosophy would arouse the curiosity of readers without the mathematical training to appreciate the

[26] Thomas Digges, "Perfit description," in Leonard Digges, *Prognostication* (1576), fol. M1v.

[27] Thomas Digges, "Perfit description," in Leonard Digges, *Prognostication* (1576), fol. M1r.

technical demonstrations of terrestrial motion.[28] The second stage, never completed, was to be a mathematical treatise on terrestrial motion. Digges declared his intent to write such a book in the preface to "Perfit description," and included it among his list of books in progress published with *Stratioticos*:

> *Commentaries* vpon the *Reuolutions* of *Copernicus*, by euidente Demonstrations grounded vpon late *Obseruations*, to ratifye and confirme hys *Theorikes* and *Hypothesis*, wherein also Demonstratiuelie shall be discussed, whether it bee possible vpon the vulgare *Thesis* of the Earthes *Stabilities*, to delyuer any true *Theorike* voyde of such irregular Motions, and other absurdities, as repugne the whole *Principles* of *Philosophie* naturall, and apparent groundes of common *Reason*.[29]

"Lawe-Brables," as he termed them in 1579, prevented Digges from devoting his full energies to completing the commentary on *De revolutionibus* or his other promised books. He became active in politics in the 1570s, about the time he began publishing. In 1572 and 1584 he was selected as MP, and from 1585 to 1588 he served as muster-master for an English expedition to the Netherlands, until he was discharged for pursuing his duties with excessive zeal. He found time to write two books on the military campaigns of his patron Leicester and to bring out new editions of two mathematical works, but he spent the last years of his life in a suit with a dishonest publisher.[30]

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[28] Thomas Digges, "Perfit description," in Leonard Digges, *Prognostication* (1576), fol. M1r-v, N4r.

[29] Thomas Digges, in Leonard Digges, *An Arithmeticall Militare Treatise, named Stratioticos*... (London: Henrie Bynneman, 1579), a4r; the earlier promise is in *Prognostication* (1576), fol. M2v.

[30] Thomas Digges alludes to delays in writing in Leonard Digges, *Stratioticos*, a4v; for details of the law-suit see Johnson, "The Complaint of Thomas Digges," in *Elizabethan and Jacobean Studies: Presented to Frank Percy Wilson in Honour of His Seventieth Birthday* (Oxford: Clarendon Press, 1959), 36-41.

Making Nautical Astronomy English

As the establishment of the Muscovy Company shows, in the early 1550s England was in a position to begin establishing itself as a sea power in command of the new mathematically-based methods of oceanic navigation. Sebastian Cabot had brought with him years of experience as *piloto mayor* at Seville, while John Dee had started to train a generation of mathematical protégés. A third factor was the privileged relationship England briefly enjoyed with Spain, whose mariners had come to rival those of Portugal in their mastery of the navigational secrets of the heavens. When the expedition to find a northeast passage to Cathay left under the command of Hugh Willoughby, Edward VI was still England's nominal monarch, with the strongly Protestant duke of Northumberland as Protector. When the survivors of the expedition returned in 1554, led by pilot general Richard Chancellor, Edward had died and Northumberland had failed in his attempt to bypass the succession by placing his young daughter-in-law Jane Grey on the throne. Once Mary ruled the country, she promptly returned England to Catholicism and went about allying England to Spain. Philip, a distant relative, was already the Spanish regent when they married; he became king after his father's abdication in 1557.

Because England was very much the junior partner of the European superpower Spain, some of the English feared, not without justification, that national interests would be subordinated to a Spanish agenda. In the matter of exploration, the alliance enabled a mutually beneficial exchange and granted the English privileged access to Spanish naval practices normally guarded as state secrets. Whereas Spanish exploration up to the 1550s had focused on the lower latitudes, the English had enjoyed moderate success in the north Atlantic. Mary and Philip secretly arranged the exchange; an English navigator would visit the *Casa de la Contratación* to observe the training of Spanish pilots and to share his own knowledge of sailing in Arctic regions. Cabot died in 1557 and would have had nothing to learn from the institution where he had worked for decades; Chancellor had died on another northern voyage in 1556. Fortunately the English had another knowledgeable pilot in the person of Stephen Borough (1525-1584), who had accompanied Chancellor on voyages to Russia in 1553-54 and 1556-57. In 1558 Borough traveled to Seville, where he carefully studied the organization of the *Casa*. His later proposal for the creation of a similar institution in England with himself as pilot-major never came to pass; however, he did become master of the Trinity House, which fulfilled some of the functions of centralizing maritime activities.[31]

Mary died and Elizabeth inherited the throne in the year of Borough's visit to the *Casa*. English relations with Spain remained cordial in the early years of the younger sister's reign, but the two countries could not continue sharing state secrets without a close alliance such as that created by a royal marriage, and so there were no more trips to Seville. Fortunately Borough had brought back with him something no less crucial to the flourishing of Spanish navigation than the well-defined structure of the House of Trade itself: a copy of the *Breve compendio de la sphera y de la arte de navegar* (1551, 1556) by Martín Cortés. The *Casa* employed the *Breve compendio* as a textbook of the methods of astronomical navigation, though it did not, of course, reveal carefully guarded knowledge such as the routes to recently discovered Spanish lands. Recognizing the advantage to be gained by training English pilots with this book, Borough persuaded the Muscovy Company that a translation would be to their benefit.

[31] For Borough's activities see *DNB* 6:668-69; and Waters, *Art of Navigation*, 103-108, 513-16.

The governors of the company commissioned a translation from Richard Eden (ca. 1520-1576), who had a background in trade and a proven track record in advocating expansion.[32] Eden had been born to a family of cloth merchants and attended the University of Cambridge, where he was granted an M.A. in 1544. After a brief stint as an alchemist illegally searching for the secret of the philosopher's stone, he became secretary to William Cecil, secretary of state and privy councilor. Northumberland had adopted an expansionist policy and was seeking to recruit cosmographers and skilled pilots. Eden probably was recommended for the position through the humanist mathematician Thomas Smith, who had been his teacher at Cambridge. Smith was a friend of the king's mathematical tutor, John Cheke, and had the connections to provide a recommendation for his friend and former pupil.

Eden dedicated his first translation, *Of the newe India* (1553) to Northumberland. His timing was extraordinarily unfortunate, since he published in the year of his chosen patron's failed coup. He preserved his own standing through strong protestations of loyalty to the new queen. To this end he prepared a new translation with a title indicating his strategy of glorifying the queen and her new husband: *The decades of the newe world or west India conteynyng the nauigations and conquestes of the Spanyardes, with the particular description of the most ryche and large landes and ilandes lately founde in the west ocean perteynyng to the inheritaunce of the kinges of Spayne* (1555). The translations, compiled from several geographical and cosmographical books, were among

[32] The standard biography of Eden is David Gwyn, "Richard Eden: Cosmographer and Alchemist," *Sixteenth Century Journal* 15 (1984): 13-24. For analysis of his publishing activities see also John Parker, *Books to Build an Empire: A Bibliographical History of English Overseas Trade to 1620* (Amsterdam: N. Israel, 1965), chapter 3, "Richard Eden: Propagandist for Empire," 36-53; and Parker, *Richard Eden: Advocate of Empire*, James Ford Bell Lectures 29 (Minneapolis: The Associates of the James Ford Bell Libraries, University of Minnesota, 1991).

the first examples of travel accounts published in England and among the first to describe English voyages of exploration. Elizabethan literature preoccupied itself with themes of travel and discovery inspired by accounts of expeditions to distant or unknown lands beginning with Eden's two books and culminating in Richard Hakluyt's massive work *The Principle Navigations, Voyages, Traffiques and Discoveries of the English Nation*, first published in 1589-90 and expanded in the edition of 1598-1600.[33]

When several members of the Muscovy Company approached Eden with a commission to translate Cortés' *Breve compendio*, he did not (so far as we know) have experience in steering a ship. They chose him because he was a competent translator educated in the theoretical underpinnings of oceanic navigation, which overlapped with cosmography and astronomy. He had also cultivated powerful patrons; Cecil had fallen out of favor under Mary but became one of Elizabeth's chief advisors after her accession in 1558. Eden's translation of the little Spanish textbook as *The Arte of Navigation* went through ten editions between 1561 and 1630, with updated tables in the later editions. It is customary to observe that the first edition was printed in a quarto format making it convenient for use at sea, whereas its Spanish predecessors had been issued in unwieldy folios.[34] Whether this was deliberate, or the fortuitous consequence of a cost-cutting decision, is perhaps impossible to tell.

While the *Arte of Navigation* includes methods that would remain current for many years, it demands less mathematical competence of pilots than some later books. I

[33] For recent historiography of travel literature see Howard Marchitello, "Recent Studies in Tudor and Early Stuart Travel Writing," *English Literary Renaissance* 29 (1999): 326-47.

[34] Eden refers to the commission in his dedicatory preface; see Cortés, *Arte of Navigation* (1561), fol. ((1r. The publishing history of the book can be found in the introduction to the facsimile version of the 1561 translation; see Waters, in Cortés, *Arte of navigation (1561)*, with intro. by D. W. Waters (Delmar, N.Y.: Scholars' Facsimiles & Reprints for John Carter Brown Library, 1992), 7-22.

chose it as the model for the Regiment of the Sun, described in chapter 6, because the rules for conversion have been simplified for the understanding of many, the full procedure being “to long and tedious.”[35] It was the first book in English on Renaissance navigation, just as its source was one of the first printed navigational textbooks in any language. English mariners of the mid-sixteenth century were less educated and less receptive to learning mathematics than later generations would be. Eden’s translation provided a guidebook for the ideal training of the Elizabethan pilot--at least, in the eyes of university-educated cosmographers and mathematicians. Its contents set a standard to be elevated, they reckoned, by the improvement of mathematics generally. Further navigational handbooks appeared in England in the following decades. William Bourne’s *A Regiment for the Sea* (first edition 1574) was the first manual to be written in English. Another *Arte of Navigation* (first edition 1581) was a translation of Pedro de Medina’s *Arte de Navegar* (1545), a book nearly as popular as Cortés’ *Breve compendio*. John Davis, an experienced sailor and explorer, first described the back-staff in still another navigational textbook, *The Seamans Secrets* (first edition 1594).[36]

The *Arte of Navigation* contains three sections on cosmology, on the Sun and Moon, and on navigational instruments. The first part is a basic *sphaera* explaining the ordering of the world and the celestial and terrestrial circles; while it is more detailed than the *Sphere* of Proclus and includes even a few tables in the geographical sections, it is more abbreviated in its treatment of astronomy than Sacrobosco’s *Sphaera*. The most prominent omission in this section is the material on risings and settings which makes up

[35] Cortés, *Arte of Navigation*, fol. 71v.

[36] On the back-staff, see Waters, *Art of Navigation*, 201-209.

nearly half of Sacrobosco's textbook. Cortés reserves the subject for the section on the luminaries, where it appears briefly in connection with the observed effects of celestial motions.

The second part of the book emphasizes prediction of apparent positions while minimizing the theoretical underpinnings of astronomy. The text explains that the regular motion of the Sun appears unequal because it is not centered on the Earth and that the inequality of lunar motion is caused by an epicycle, but neither explanation nor illustration of these concepts appears to illuminate the reader. The centerpiece of the chapters dedicated to the Sun is the calculation of solar motion, an essential step in the Regiment of the Sun, together with the necessary tables. Subsequent chapters on the Moon replace tables with a rough-and-ready method of calculating lunar motion drawn from *computus*. Further evidence of the work's dependence on *computus* literature can be found in chapters on the calendar and the basic units of time: year, month, week, day, and hour. A short discussion of the lunar influence on tides and a collection of weather lore round out the second part of the book. University students reading *sphaeras* typically came to their work with a background in the art of time-reckoning and expected (or were commanded by the statutes) to learn about the heavens and to improve their command of mathematical discipline. In contrast, the majority of the intended audience of Cortés' book knew nothing about timekeeping and cared little about astronomical theory. They wanted only to find their way from one place to another.

The last third of the book explains the making and use of instruments for navigation. Several chapters are devoted to the astrolabe and cross-staff, including the methods of converting astronomical observations into terrestrial latitude. Of the other instruments mentioned, the lodestone and compass, along with the sea-chart, received the most attention from Elizabethan philosophers and mathematicians. Exploration and geography enjoyed a mutually beneficial relationship in the Renaissance period. At the *Casa* in Seville, for example, Cabot and other cosmographers provided Spanish ships with charts reflecting the best geographical knowledge of the time. The pilots in return mapped out newly discovered lands and improved their charts of known coastlines. Their work was incorporated into the master chart kept by the *piloto mayor*. English mathematicians devoted their energies to the problem of representing distant lands. When John Dee returned from his early travels in Europe, he brought globes made by Mercator. For many years he promoted the search for a northeast passage to Cathay, which did not end with the founding of the Muscovy Company.[37]

A school of studies of magnetism developed in Elizabethan England partly in hopes of discovering the underlying workings of the compass. Magnetized iron had entered European navigational practices in the Middle Ages prior to the introduction of nautical astronomy. Around the fifteenth century sailors became aware of the phenomenon of magnetic declination, or variation. On most of the Earth, magnetic north is not identical with geographical north. The difference causes compass needles to point slightly away from true north, but variation could be accommodated so long as ships remained in a circumscribed area. In the Mediterranean, where the ship sailed according to a portolan chart, navigators ignored variation. Mapmakers drew charts based on the compass and did not correct for variation. While the resultant maps were distorted according to modern standards, compasses would indicate the correct bearing on the map.

[37] Taylor, *Tudor Geography*, 75-139.

Compass makers in northern areas, where charts were less important, adjusted for variation by attaching the compass card, with the directions marked on it, at an angle to the magnetized iron.[38]

Problems were bound to occur when voyages of discovery left the regions where stopgap remedies for variation had been devised. The English instrument maker Robert Norman, in *The Newe Attractive* (1581), described the tendency of a balanced compass-needle to "dip" once it has been magnetized. He also warned against the use of realigned compasses and charts made with such instruments. Since adjustments varied with region and with the individual maker, combining instruments with different corrections could lead the ship astray. Richard Eden's final publication *A very necessarie and profitable booke concerning navigation* (1579?), a translation of John Taisnier's *De natura magnetis*, began with a series of magnetic tricks to be performed with a lodestone. The English title is actually more accurate than the French, for most of the book concerns ships and sailing and not magnetism *per se*. Eden prepared it as a companion to the *Arte of navigation*, and the two books sometimes appear together. The culmination of magnetic studies in Elizabethan England was William Gilbert's *De magnete* (1600), which concluded that the Earth as a whole was magnetic.[39]

Thomas Digges included a short essay on variation with the "Perfit description" added to later editions of his father's *Prognostication*. According to the main theories of magnetism, the lodestone was attracted either by a magnetic mountain in the north or else by a magnetic point in the heavens. Digges critiques both theories. On the one hand, there

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[38] Waters, *Art of Navigation*, 24-25.

[39] For the publication of Eden's last book see Gwyn, "Richard Eden," 34. For an account of Gilbert's place in English magnetism see Duane H. D. Roller, *The De Magnete of William Gilbert* (Amsterdam: Menno

can be no single "attractive point" on the Earth because the meridians aligned with the compass needle in different locations do not converge on a single point. On the other hand, there cannot be an attractive point in the sky because the diurnal rotation of the heavens or the Earth would cause variation in a single location to change over the course of a day. Variation is "no question for grosse mariners to meddle with, no more then the fyndinge of the *Longitude*." In a brief digression he attacks Sebastian Cabot and others who, without mathematical expertise, claim to have solved the problem of finding longitude; it requires arithmetic and geometry, which are "the onlye wynges to eleuate oure grosse senses to matters so highe and misticall." Digges promises in future to reveal his own method involving eclipses.[40]

After a confusing attempt to account for variation, Digges identifies six "Errors in the Arte of Nauigation commonly practized." First, he says, charts distort geography by making meridians of longitude parallel when they should converge at the poles. Second, mariners assume that a ship oriented to rhumb lines, which represent the compass points, will follow a great circle, when in fact it will gradually spiral toward the pole. Third, the value used to adjust the altitude of Polaris, according to the Regiment of the North Star, is not correct in all latitudes. Fourth, the cross-staff introduces error into the latitude, since the end when it rests on the cheekbone is not brought exactly to the center of the eye. The art of perspective demonstrates that the attempted correction of paring away a bit of the end increases the error. Fifth, geometry demonstrates that the rules for converting a degree of latitude to distance traveled are in error. Finally, since navigators have no rule

Hertzberger, 1959).

[40] Thomas Digges, in Leonard Digges, *Prognostication* (1576), fol. O3v-O4r. On his deathbed, Cabot told Eden that God had revealed to him the secret of longitude; Gwyn, "Richard Eden," 31.

for finding longitude, ships must wait out the night far out at sea rather than approach a coastline or harbor at night. The practice saves ships from running aground, but it adds an unnecessary expense and exposes ships to other dangers.[41]

Digges' patronizing attitude toward mariners virtually guaranteed that he would receive no respect in turn for his attempts to improve navigation. Besides advising that "grosse mariners" should not put forth uninformed opinions on the solution of latitude, he considered their reports of experience to be unreliable. "If there were any truste to ye obseruation of mariners," he lamented, he could confirm his explanation of variation, but he "found by experience their grosse vsage and homelye instrumentes . . . and also their repugnaunt tales" did not suit his purpose.[42] His attempts to rectify navigation along mathematical lines met with a poor reception. In the *Stratioticos*, published a few years later, Digges mentions his proposals and the reaction among mariners, who were as hostile as the soldiers to whom he suggested reforming the army along classical lines.

> First therefore, by *Demonstrations Mathematical* finding the great imperfections in the Arte of *Nauigation*, & grosse Errours practised by the masters and Mariners of this our age, I sought by reason to perswade with some of them to alter & reforme their *Chartes*, *Instruments*, and erronious *Rules*, shewing them infallible Demonstrations of their *Errours*. . . . [But] by *Masters*, *Pilotes*, and *Mariners*, I haue bene aunswered, that my *Demonstrations* were pretie deuises: but if I had bene in any Sea seruices, I should finde all these my *Inuentions* mere toyes, & their Rules onely practizeable: Adding farder, that whatsoeuer I could in *Paper* by Demonstations perswade, by Experience on *Seas* they found their *Chartes* and *Instruments* true and infallible. . . . I spent a xv. weekes in continual *Sea* seruices vpon the Ocean, where by proofe I found, and those verie *Masters* themselues could not but confesse, that *Experience* did no lesse plainely discouer the *Errours* of their Rules, than my *Demonstrations*.[43]

[41] Thomas Digges, in Leonard Digges, *Prognostication* (1576), fol. P1r-P2r. Loxodromes, or lines spiraling towards the pole, created by applying rhumb lines to a sphere, were described by Pedro Nuñez in the sixteenth century. The method of trimming the cross-staff was proposed by Bourne, *Regiment for the Sea*, 209.

[42] Thomas Digges, in Leonard Digges, *Prognostication* (1576), fol. P1r.

[43] Thomas Digges, in Leonard Digges, *Stratioticos*, fol. A3v, A4r-v.

Richard Eden had complained of sailors who had more admiration for the localized knowledge of fisherman frequenting the Thames than for expert pilots able to find their way without rutter or chart.[44] The candid account of Digges reveals another side of the situation. While practicing pilots and sailors resented his intrusion into their craft, we can see that they practiced oceanic navigation, since they use cross-staves, find their latitude from the North Star, and know about latitude. Ending his tale with the recognition of his accomplishments by the experts is self-serving but not necessarily false.

I shall conclude my discussion of Elizabethan navigation by returning once again to John Dee, who tirelessly promoted mathematical studies of all sorts to his countrymen by taking on pupils, by amassing a sizable collection of books for his library, and by describing the advantages the mathematical arts had to offer. His "Mathematicall Praeface" to Henry Billingsley's translation of Euclid's *Elements* (1570) surveyed the many sciences founded upon arithmetic and geometry. Navigation, of course, is among them. The master pilot must know not only astronomy and astrology, but hydrography (the geography of the oceans) and horometry (the art of time-telling); he must be able to apprise the worth of his instruments, calculate the motions of the planets, find his longitude and latitude from celestial bodies, and forecast weather by heavenly signs as well as animal behavior. England ought to be concerned above all other nations with the abilities of its pilots, he concludes, "by reason of Situation, most commodious for *Nauigation*, to Places most Famous and Riche."[45]

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[44] Eden, in Cortés, *Arte of Navigation*, fol. (4v-((1r.

[45] Dee, *The Mathematicall Praeface to the Elements of Geometry of Euclid of Megara (1570)*, with intro.

Dee extended his advocacy of English navigational studies in *General and Rare Memorials pertayning to the Perfect Arte of Navigation* (1577), a curious combination of antiquarianism, nationalism, and practicality. Intended as the first in a series of books laying out a plan of British imperialism, the *Memorials* outline the role of ships and seafaring in defending and magnifying the country's greatness with a proposed standing "Pety-Navy-Royall" as the centerpiece.[46] Dee enumerates many advantages that would accrue from the maintenance of a standing navy: Britain's shores would be secure from raiders and invaders and its merchant ships would be protected from pirates; many of the sailors would become experienced pilots, captains, and marines to form the core of a larger navy in times of war; idle people would be usefully employed; local fisheries would be exploited by British ships rather than foreign ones; and so on. He proposes further that the government support a group of experts to provide the navy with education in a variety of skills, including nautical astronomy, foreign languages, and mechanics.[47]

Despite the frustration evident in the efforts of Digges and Dee to convince their audiences to embrace an elite and erudite approach to navigation, the English maritime community had come a long way by the 1570s. Up to that point, gentlemen and college graduates had led the way in advocating and furthering the practice of oceanic navigation; soon their ranks would be joined by craftsmen and self-educated practitioners such as Bourne, Norman, and Davis, whose books on navigation and magnetism have

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by Allen G. Debus (New York: Science History Publications, 1975), fol. A1r. For the place of the preface in Elizabethan intellectual history see the introduction by Debus.

[46] Yates, *Astraea: The Imperial Theme in the Sixteenth Century* (London: Routledge & Kegan Paul, 1975), 48-51.

[47] Dee, *General and Rare Memorials pertaying to the Perfecte Arte of Navigation* (London: 1577). Sherman, *John Dee*, 152-71, summarizes the *Memorials* and their impact.

been mentioned briefly. Digges attempted a partnership between the groups but failed, perhaps because of his arrogance. Dee met with more success, beginning with his position as advisor to the Muscovy Company; in the 1580s he was still providing expeditions with charts and mathematical instruction. Edward Wright and Thomas Harriot, two outstanding mathematicians of the late sixteenth century, followed Dee's example of close association with mariners. Harriot gave lectures to ship captains and accompanied his patron, Walter Raleigh, on an expedition to Virginia. Wright, like Digges, worked on remedying the shortcomings of navigation that he observed on board ship, publishing the results as *Certain Errors in Navigation* (1599).[48]

By the end of the Elizabethan era, oceanic navigation had become a native tradition for the English that united the subjects of magnetism, geography, and astronomy. Most English mathematicians found some way to make their own contributions to the growing body of work on the pilot's art. The simultaneous publication by Thomas Digges of the "Perfit description" and the "Errors in the Arte of Nauigation" illustrates that astronomy and navigation were closely connected in the minds of practitioners of the exact sciences.

[48] John W. Shirley, "Science and Navigation in Renaissance England," in *Science and the Arts in the Renaissance*, ed. John W. Shirley and F. David Hoeniger (Washington: Folger Shakespeare Library; London and Toronto: Associated University Presses, 1985), 74-93.

Elizabethan Mathematical Popularizers

In the last chapter I described two early English-language publications that included material on astronomy, namely Caxton's translation of *Myrrour of the worlde* and the frequently-translated *Kalender of Shepherdes*. By the end of the sixteenth century minor mathematical practitioners and well-informed nonpractitioners had turned out a host of scientific popularizations alongside the publications of prominent figures like Dee. As examples of such works I have chosen the astronomical textbooks of three mathematical popularizers: Thomas Hill, John Blagrave, and Thomas Blundeville. Blagrave was a surveyor who published several books on mathematical instruments. In contrast to Blagrave, neither Hill nor Blundeville was a practitioner, but both had acquired some competence in astronomy and cosmography. They produced books for popular consumption on diverse subjects ranging from divination to gardening to dressage and frequently compiled or translated from other authors. All three are remembered primarily as popularizers who made existing ideas readily available to a large audience.

Little is known about Thomas Hill (ca. 1528-ca. 1574) beyond biographical comments in his books.[49] His first publication, a translation of a work on physiognomy, appeared in 1556; he continued to publish and to prepare books for publication until his death around 1574. Two of his books, *The Contemplation of Mankinde* (1571) and *The proffitable Arte of Gardening* (1568) include lists of books published, books near publication, and books in progress. After his death, his friends compiled some of his manuscripts and perhaps completed them for posthumous publication. His chosen

[49] For biography of Hill see *DNB* 27:196-97; for his publication history see Johnson, "Thomas Hill: An Elizabethan Huxley," *Huntington Library Quarterly* 7 (1943-44): 329-51.

subject-matters cannot be characterized easily, but they include Paracelsian divination, assorted methods of divination, and gardening; among his most popular books was a compilation, *The Gardeners Labyrinth*, published in 1577 under the literary pseudonym Didymus Mountaine. He also prepared several almanacs.

The last new work to be published in Hill's name was *The Schoole of Skil* (1599), based on a manuscript titled *The Rudiments of the Sphere*. William Jaggard, a printer best known for producing Shakespeare's first folio, had been an apprentice to Henry Dernham, who had printed other works for Hill. Jaggard most probably found the manuscript at Dernham's shop and arranged to have it printed after being informed of its potential appeal as a mathematical textbook.[50] The full title of the work gives some indication of its contents:

> *The Schoole of Skil: Containing two Bookes: The first, of the Sphere, of heauen, of the Starres, of their Orbes, and of the Earth, &c. The Second, of the Spherical Elements, of the celestiall Circles, and of their vses, &c.*

It is easily recognized as a typical specimen of the *sphaera* genre in two parts. The first part explains the basic Ptolemaic cosmology drawn from mathematical and physical principles. The second part begins with the circles represented by an armillary sphere, describes the constellations and some of their astrological influences, then strays into geography, with about a fifth of the book devoted to sample geographical problems before returning to the traditional *sphaera* subject of zones, which concludes the book.

We might reasonably expect to find Hill's *sphaera* listed among his forthcoming publications or works in progress. However, while no work is described precisely as

[50] Jaggard tells part of the story in the letter to the reader; see Hill, *The Schoole of Skil* (London: T. Iudson, for W. Iaggard, 1599), fol. A3r-A4v. On Jaggard see *DNB* 29:585; for his connection to Dernham see Johnson, "Thomas Hill," 334-35.

"rudiments of the sphere," several must have incorporated the subject in some manner. A few can be eliminated. For instance, Hill describes the "Treatyse of the Sphere, right profitable for Mariners" as a compilation based in part on Stöffler's Proclus commentary (one of Recorde's sources), but the *Schoole of Skil* bears no resemblance to Stöffler. Possibly Jaggard even combined parts of different manuscripts.[51] One candidate appears in a list of books "now in a readynesse to be imprinted and the most of them with the Printers":

> A pleasaunt Treatise, intituled the Pathe way to knowledge, teaching all such principles, as necessarilie sarue to the better vnderstanding of the arte of Astronomie, and Astrologie, with other pleasaunte rules besydes annexed, and that right proffitable, the which looke for at the handes of the sayd Suttone [i.e. Edward Suttone, a printer named earlier].[52]

The title *Pathway to Knowledge* may have been inspired by one of Recorde's textbooks. A second candidate comes from Hill's other list:

> A paradoxall Compasse, contayning a large description of all the celestiall Cyrcles of the Sphere: a marueylous order taught in the motions of them, with the infinite vses that these serue vnto, for the knowledge of the true distaunce of places . . . and a large description of the Celestiall ymages, lying aswell on the North, and South side of the equatour, as of the Ecclipticke: with the rysing and setting, of the fixed Starres .&c. gathered out of the best and latest wryters in our tyme, and in a maner readie to the printing.[53]

Most of the geographical material in the *Schoole of Skil* consists of methods for finding distances between places; it is associated with a catalogue of constellations. In the "Mathematicall Praeface," the *General and Rare Memorials*, and elsewhere, Dee mentioned his invention of a "paradoxall Compasse." Its secret has been lost, but it may

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[51] Johnson, "Thomas Hill," 340 n. 29, 346.

[52] From Hill, *Proffitable Arte of Gardening* (1968), quoted in Louis Wright, *Middle-Class Culture*, 566 n. 30. The note quotes the list in full, including the "Treatyse of the Sphere" also mentioned above.

[53] From Hill, *Contemplation of Mankind*, quoted in Johnson, "Thomas Hill," 349-50. Johnson quotes the list in full.

have involved a solution to the problem of the spiraling loxodromic curves in Digges' list of navigational errors. Dee assisted Hill in revising his book on physiognomy and may have shared information with him about the paradoxall compasse, but the invention does not figure in the *Schoole of Skil*.[54]

In large part because of historian Francis R. Johnson, who managed to frame the history of Tudor astronomy as a catalogue of early responses to Copernicanism both *pro* and *con*, Hill has been turned into one of the canonical minor figures of the period, because his otherwise unremarkable little textbook contains one of the longest responses to Copernicus published in English before 1600. Both forms of terrestrial motion, diurnal and annual, are firmly rejected on the basis of astronomical observations, scripture, and physics. The book also adopts parameters of Copernican astronomy where they are not in conflict with geocentrism. Copernican distances for the Sun and Moon are given. For precession, the Copernican period of 25,916 years is preferred. Later, the book provides a miniature history of observations of the obliquity of the ecliptic that ends with Copernicus' libration theory of trepidation: the obliquity varies over 0;24° with oscillations of 1,717 and 3,434 Egyptian years.[55]

Taken as a whole, *The Schoole of Skil* creates the impression of conservative cosmology but also an informed attitude toward recent astronomical discoveries on the part of a typical textbook author, but such a conclusion must be qualified. With the exception of the anomalous geographical material and the astrological star catalogue, most of Hill's book comprises a previously unrecognized translation of extracts from

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[54] For Dee's advice to Hill see *DNB* 27:197.

[55] Hill, *Schoole of Skil*, 42-51 (Copernicus refuted), 26-28 (solar and lunar distances), 19 (precession), 113-14 (trepidation).

Peucer's *Elementa doctrinae de circulis coelestibus*, including the assorted notices of Copernicus.[56] Johnson admits in a limited sense that Hill is a compiler, but his short discussion creates the impression that the English author's presentation, if not his ideas, are original. Possibly even Jaggard and his contemporaries did not connect Hill with Peucer, since the preface treats the clarity and sensible ordering of the book as qualities attributable to Hill. Other modern commentators have treated the book as an unproblematic indication of Hill's beliefs.[57] Very probably it is, since he could have simply excised anything not meeting with his approval, but it is worth remembering that he need not have digested a great deal of material or understood anything of Copernicus past what he found in a single textbook for arts students.

Probably the only material in *The Schoole of Skil* to have received any attention in modern times is the anti-Copernican material, which, because of its complex origins as well as its historiographical significance, calls for a short treatment here. The passage begins with a history lesson:

> *Aristarchus Samius*, which was 261 yeares, before the byrth of Christ, tooke the earth from the middle of the world, and placed it in a peculiar Orbe, included within *Marses* and *Venus* Sphere, and to bee drawne aboute by peculiar motions, about the Sunne, which hee fayned to stande in the myddle of the worlde as vnmoueable, after the manner of the fixed stars. The like argument doth that learned *Copernicus*, apply vnto his demonstrations.[58]

[56] Compare Peucer, *Elementa doctrinae* (1569), 100-107 (Copernicus refuted), 84-86 (solar and lunar distances), 78 (precession), 152-53 (trepidation). I have not yet identified Hill's other source or sources, if any exist; one possibility for the geographical material, which uses German miles and European cities as examples, is a book on geography by Peucer.

[57] Johnson, *Astronomical Thought*, 183-85; see also Paul H. Kocher, *Science and Religion in Elizabethan England* (San Marino: Huntington Library, 1953), 163, 193; and John Russell, "Copernican System in Britain," 198 (who simply quotes Hill without comment). Rosen, "Galileo's Misstatements about Copernicus," *Isis* 49 (1958): 324 and 325 n. 35, quotes both authors and notes the similarity of their approaches, but does not realize that Hill's "offend and trouble the young students in the Art" is the same as Peucer's "lest beginners be offended or disturbed by the novelty of his hypotheses" (Rosen's translation).

[58] Hill, *Schoole of Skil*, 42.

Compare the opening of the corresponding passage in Peucer:

> ARISTARCHVS Samius, qui ante annos mille octingentos uixit, terram medio mundi exemptam, & orbi peculiari inclusam, intra Martis & Veneris sphaeram collocauit, & motibus circumagi peculiaribus circa Solem in mundi medio immotum, more stellarum finxit. Et similes hypotheses Copernicus omnium, qui post Ptolemaeum de doctrina Astrorum scripserunt summus, ad suas demonstrationes assumpsit.[59]

Like most Elizabethan translators, Hill has altered the original in minor ways, by converting the date for Aristarchus and condensing a comparison of Copernicus and Ptolemy to the single word "learned." Otherwise his rendering is quite close, as is typical of the book as a whole.

Between the introduction and the list of observationally based objections to terrestrial motion, Hill has inserted a second list of unknown origin, which for the most part duplicates Peucer's more detailed refutations. Probably he has taken it from another source rather than writing it himself, since it uses the value of fifteen German miles for a degree of longitude. The remainder of the passage, from the heading "If the Earth be not in the middle of the Worlde," has Peucer's *sphaera* as its immediate source. But as we saw in chapter 5, Peucer himself wrote the introduction but extracted most of the refutations from Melanchthon's *Initia doctrinae physicae*. An extended attack on heliocentrism, published in London in 1599 and long treated as representative of the Elizabethan reaction to Copernicus, actually had its genesis in a physics textbook in Wittenberg in 1549.

John Blagrave (a. 1560-1611) was a self-taught practitioner; he worked as a

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[59] Peucer, *Elementa doctrinae* (1569), 100-101.

surveyor and published descriptions of instruments, including a few of his own design.[60] Two of his books are especially relevant to astronomy. The first is *The Mathematical Iewel* (1585), describing the manufacture and use of an astrolabe based partly on Gemma Frisius. The function of an astrolabe is to represent the sky as seen from the Earth, so by nature it must be geocentric if it is to be at all practical. However, Blagrave inserts a seemingly gratuitous mention of heliocentrism into a passage about the many centers and circles of planetary motion, raising the question of whether they can be resolved by the Copernican system. In chapters following Gemma Frisius, Copernicus' trepidation model receives the usual positive notices.[61]

A decade later, Blagrave published a sequel to the *Mathematical Iewel* describing an astrolabe of his own design entitled *Astrolabium Uranicum Generale* (1596). The novelty of the instrument appears on the title page: "Agreeable to the Hipothesis of Nicolaus Copernicus, the Starry Firmament is appointed perpetually fixed, and the earth and his Horizons continually mouing from West toward the East once about every 24 houres." Blagrave has accommodated Copernicanism by making the *rete* of the astrolabe, a plate carrying the stars, fixed and motionless, while rotating the *mater* depicting the horizon of the observer, a reversal of the usual design of astrolabes. He is clearly sympathetic to the concept of terrestrial rotation, but whether he is equally open to heliocentrism cannot be determined from his astrolabe design.[62]

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[60] For biography of Blagrave see *DNB* 6:63-64.

[61] Blagrave, *The Mathematical Iewel, Shewing the making, and most excellent use of a singular Instrument so called*... (London: Walter Venge, 1585), 11 (Copernican system described), 25 (Copernicus found decreasing obliquity of ecliptic), 32 (Copernicus found inequality of precession). Johnson, *Astronomical Thought*, 313, describes the astrolabe as Blagrave's invention, but his dependence upon Gemma Frisius is clearly indicated through much of the book.

[62] For a short description of Blagrave's Copernican astrolabe see Johnson, *Astronomical Thought*, 208-210.

The last subject of the *Astrolabium Uranicum* is the observation of comets with the astrolabe. Not only the nova of 1572 but a series of notable comets in the 1570s and 1580s had directed attention skyward. Blagrave read at least two books on the question of whether these phenomena were located beyond the Moon:

> Because I haue seene some 4 or fiue yeares past a book entituled *Noua theoria Cometarum* as I remember, set foorth by on *Reslyn*, who taking occasion vppon that great Comet or Blazing-Starre, which *Anno 1570* was seene so long in the Constellation of *Cassiopeia*, in a manner fixed without motion, to imagining therefore that Comet to happen in the very Pole of the *Theoricke*, and that to be the cause why he mooueth not, thereupon runneth on a course, with recitall of diuerse Comets and their motions, but concluted no certaintie to my remembrance, ending his booke with this saying, *Est quodam prodire tenus si non datur vltra*. But our late learned countreyman Mayster *Digges*, in his *Scala Mathematica* found, because he had no Parallax, that he must needes be beyond the Speere of the [Moon].[63]

Blagrave has conflated at least two episodes. Digges wrote the *Alae seu scalae mathematicae* on a new star, not a comet, that appeared in 1572, not 1570. The other book he mentions is the *Theoria nova coelestium meteoron* (1578) of Helisaeus Röslin, a graduate of the University of Tübingen. When the comet of 1577 appeared, he came to the conclusion shared by many contemporary astronomers that it was located in the celestial realm. In the *Theoria nova* he assigned all comets to a previously undetected shared sphere. The quoted conclusion comes from Horace and means “It is worth while to take some steps forward, though we may not go still further,” which Blagrave aptly summarizes as showing “no certaintie.”[64]

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[63] Blagrave, *Astrolabium Uranicum Generale. A Necessary and Pleasaunt solace and recreation for Navigators in their long Iorneying, Containing the use of an Instrument or generall Astrolabe*... (London: Thomas Purfoot, for William Matts, 1596), fol. I1r-v.

[64] Horace, *Satires, Epistles, and Ars Poetica*, transl. H. Rushton Fairclough, Loeb Classical Library (1929), *Epistles* 1, p. 253. On Röslin see Miguel A. Granada, *El debate cosmológico en 1588: Bruno, Brahe, Rothmann, Ursus, Röslin* (Naples: Bibliopolis, 1996), 109-161; and for his work on the comet see Hellmann, *Comet of 1577*, 159-73.

Thomas Blundeville (1522?-1606?) published popular works on various subjects of interest to the middle class; like Hill, he took a special interest in mathematics.[65] He wrote two books on horsemanship as well as the first English book on the study of history, and translated from Italian and Latin into English. He knew such figures of the English mathematical revival as John Dee, Henry Briggs, and Edward Wright. Several mathematical instruments are mentioned in his will. He served as a math tutor in several households.

Two of Blundeville's publications are mathematical textbooks intended for the education of gentlemen's sons, and both claim to be equally useful to mariners. The first to appear is *M. Blundevile His Exercises, containing sixe Treatises* (1594), which went through several editions. The first "treatise" is an arithmetic textbook originally written for a private student. The second treatise is a cosmography in two books on the celestial and elemental realms, resembling Hill's *Schoole of Skil* in structure and general contents. The remaining treatises are more specialized, including a description of Mercator's globes with Stadius' ephemerides and a short narrative of Drake's Indies expedition; a description of Peter Plancius' world map; a description of Blagrave's "mathematical jewel"; and oceanic navigation. A revised version of the *Exercises* from 1597 and later (the book went through seven editions by the 1630s) included a treatise on the use of maps and another on Ptolemy's tables of latitude and longitude, originally printed separately as *A Briefe Description of Universal Mappes and Cardes* (1589).[66]

Even in a very brief examination of the *Exercises* it becomes apparent that

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[65] For biographical information on Blundeville see *DNB* 6:345-46; and Karl-Ludwig Selig's introduction to Blundeville, *Of Councils and Counselors (1570)* (Gainesville: Scholars' Facsimiles & Reprints, 1963).

[66] Johnson, *Astronomical Thought*, 206.

Blundeville took care to keep his textbooks up-to-date. In addition to the treatises dedicated to sixteenth-century authors, contemporary references appear throughout the text. Blundeville includes an explanation of the trigonometric treatise that Clavius had appended to his commentary on the *Sphaericorum* of Theodosius. In addition to Plancius' map, he includes geographical details from the works of Gemma Frisius, Mercator, and Bourne. He distinguishes between the tropical and sidereal years, assigning the latter the Copernican length of 365d 6;9,29h, and refers to Copernicus' theory that the obliquity of the ecliptic changes over a period of 3,434 years. The sidereal year is favored as it is of unvarying length.[67]

Blundeville brings up the heliocentric system in the *Exercises* but treats it as a calculating device:

> [S]ome also deny that the earth is in the middest of the worlde, and some affirme that it is moueable, as also *Copernicus* by way of supposition, and not for that he thought so in deede: who affirmeth that the earth turneth about, and that the sunne standeth still in the midst of the heauens, by helpe of which false supposition he hath made truer demonstrations of the motions & reuolutions of the celestiall Speares, then euer were made before, as plainely appeareth by his booke *de Reuolutionibus* dedicated to Paulus Tertius the Pope, in the yeare of our Lord *1536*.[68]

Osiander's anonymous letter to the reader proposed such a reading of Copernicus. Thomas Digges wrote the "Perfit Description" in part to prove to his countrymen that Copernicus intended his system as physical reality and not just mathematical convenience. Giordano Bruno lectured on Copernicus at Oxford in 1583, ending up in a debate with the conservative English scholars. In *Cena de le Ceneri* (1584), his

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[67] Blundeville, *M Blundevile His Exercises, containing sixe Treatises, the titles whereof are set down in the next printed page*... (London: John Windet, 1594), fol. 144v (obliquity of ecliptic), 168v-169r (types of years defined), 343r-v (Copernicus identified as authority on year length).

[68] Blundeville, *Exercises* (1594), fol. 181r.

fictionalized retelling of the event, one of the debating points is whether Copernicus advocated terrestrial motion, with Bruno rightly dismissing the letter as a spurious addition.[69] If Blundeville, whom we might regard as a well-informed layman in mathematics, still regarded heliocentrism as a fiction in 1594, Digges' efforts cannot have made much impact. Blundeville's knowledge of the book is patchy: he is aware of the dedication to the pope but misdates it, and perhaps *De revolutionibus*, to 1536, actually the date of Cardinal Schonberg's letter to Copernicus urging him to publish.[70]

Blundeville's other major mathematical publication was *The Theoriques of the seuen Planets* (1602), the first *theorica* to be printed in English (a treatise on the *equatorium*, which might be considered a *theorica*, had circulated in manuscript in the late Middle Ages).[71] The letter to the reader justifies the publication by reference to the enthusiastic reception among gentlemen of his *Exercises* teaching introductory geography and astronomy.

> I thought I could not shew my selfe any way more thankfull vnto them, than by setting forth the Theoriques of the Planets, vvich I haue collected, partly out of *Ptolomey*, and partly out of *Purbachius*, and of his Commentator *Reinholdus*, also out of *Copernicus*, but most out of *Mestelyn*, whom I haue cheefely followed, because his method and order of writing greatly contenteth my humor. I haue also in many things followed *Maginus*, a later vvriter, vvho came not vnto my hands, before that I had almost ended the first part of my booke, neither should I haue had him at all, if my good friend M. Doctor *Browne*, one of the ordinarie Physicians to her Maiestie, had not gotten him for me. . . .[72]

Blundeville's litany of names is misleading. Most of the first part is a translation from

[69] Gatti, *Giordano Bruno*, 54-55.

[70] *De rev.* (1543), fol. ijr.

[71] *The Equatorie of the Planetis*, sometimes attributed to Chaucer.

[72] Blundeville, *The Theoriques of the seuen Planets, shewing all their diuerse motions, and all other Accidents, called Passions, thereunto belonging* (London: Adam Islip, 1602), 1-2.

Maestlin's *theorica*, in the fourth book of his *Epitome astronomiae*, interspersed with a few sections from Reinhold's commentary on Peurbach's *Theoricae novae*.[73] If the writings of Ptolemy or Copernicus have entered into the book, I have not been able to find them, but Maestlin explains astronomical models for both authorities. Blundeville did not need Maestlin's *sphaera* because his own *Exercises* covered the material.

The rest of the book consists of an extract from the *Novae coelestium orbium theoricae congruentes cum observationibus N. Copernici* (1589) of Giovanni Antonio Magini and instruments described by William Gilbert in *De magnete*, billed on the title page of the *Theoriques* as "two most ingenious and necessarie Instruments for Sea-men, to find out thereby the latitude of any Place vpon the Sea or Land." It is easy to see why Magini's *theorica* caught Blundeville's attention: its author has converted the Copernican planetary models to a geocentric framework and presented them in terms of three-dimensional orbs, the method popularized by Peurbach over a century earlier. Magini accounted for the motions of the Earth by transferring them to the outer spheres: the eleventh sphere (counting outward) causes daily rotation; the tenth and ninth cause the librations; and the eighth sphere bearing the fixed stars causes precession. Blundeville considers Magini's approach to be a great advantage:

> To auoid the Paradoxicall supposition of *Copernicus*, supposing the Earth to mooue, and the Sunne to stand still in the middest of heauen, *Maginus* is fain to suppose that there be three mouable heauens aboue the eight heauen, and so maketh in all eleuen mouable heauens. . . . Of which his Theoriques I thought good to make a breefe Extract, because that more tearmes belonging to the Prutenicall Tables are therein both defined and demonstrated, than are set downe either by *Purbachius* or by *Mestelyn* in their Theoriques.[74]

[73] The *Theoriques* is correctly identified as a translation in Louis Wright, *Middle-Class Culture*, 350, but not in the more specialized Johnson, *Astronomical Thought*, 212.

[74] Blundeville, *Theoriques*, 215. Note the similarity of phrasing to his discussion of Copernicus in the *Exercises*, quoted earlier, where the word "supposition" means a hypothesis for calculation.

Peurbach worked long before the creation of the Prutenic Tables, while Reinhold, their author, died after having barely started revising his *theorica* commentary. Magini was hardly a later writer than Maestlin, as Blundeville claimed in the preface (quoted above), but his *theorica* might have appeared more current. Maestlin switched between Ptolemaic and geocentrized Copernican models indifferently and included the outdated equant.

The evidence suggests that when he decided to publish a book on planetary astronomy, Blundeville selected Maestlin as his main source because it was well written and sensibly organized. When he had nearly finished, Dr. Browne (who had shown him scientific works in the past) brought to his attention a recently obtained copy of Magini that was better suited to Blundeville's goal of preparing readers to use the *Prutenic Tables*. Rather than discard half the work, he decided to publish both together. Since the book would appeal to a small audience at best, he tried to expand its readership by appending an explanation of Gilbert's devices for navigation and by describing the whole on the title page as "A Booke most necessarie for all Gentlemen that are desirous to be skilfull in Astronomie, and for all Pilots and Sea-men, or any others that loue to serue the Prince on the Sea, or by the Sea to trauell into forraine Countries." These are exactly the groups the early Tudor humanist Rastell wanted to reach through translation: on the one hand tradesmen, namely pilots and sailors; on the other hand gentlemen, who might study astronomy either for the sake of gentlemanly accomplishment or else to understand the navigator's art while on board ship.

The *Theoriques* was not an especially successful book; only the single edition was printed in 1602. Navigators needed to predict the motions of the luminaries, but they had little use for the other planets unless they intended to practice astrometeorology. The exposition of the solar and lunar models was sketchy in standard navigational textbooks. In Eden's translation, for instance, the lunar epicycle is not explained. As for mathematical studies, it had little need as yet for advanced astronomical textbooks in English; the handful of serious practitioners must have still been willing to study Latin and read the continental texts. In the following decades the *theorica* became an obsolete form everywhere. Blundeville's *Theoriques* was the last as well as the first of its kind.

If these popularizers are at all representative, the highly educated mathematicians who wanted to create a nation of practitioners must have been constantly frustrated. Perhaps the advocates of nautical astronomy held their would-be pupils to an unreasonable level of performance. In the 1550s and 1560s a few enthusiasts struggled to persuade traditional pilots to learn an unfamiliar set of skills involving constant calculations. By the 1570s such calculations had become routine, at least among the better-educated pilots and captains. Digges became exasperated because they were content to employ the methods they had been taught, which were actually the state of the art in European navigation, rather than refining them in light of ever more esoteric mathematical concerns. Blundeville and Blagrave are themselves advocates; the difference between them and Digges is specialization and amount of training. Despite their enthusiasm for the exact sciences, they sometimes fumble with their material. Blundeville does not know when *De revolutionibus* was published and does not believe Copernicus to be a heliocentrist, while Blagrave confuses two distinct episodes of unusual celestial phenomena, one in 1572, the other in 1577. All in all, however, their work must be regarded as a significant advance over the early Tudor period.

Conclusions

The study and application of the mathematical arts in England became considerably more sophisticated over the course of the sixteenth century, and many works were available in the vernacular by the end of our period. The assimilation of books by Lutheran authors was a key ingredient in this process--which is not to say that reading texts by Lutheran mathematicians automatically increased mathematical ability! English readers considered Melanchthon's followers to be among the best modern authorities in the exact sciences and found in their works further motivation for study.

The Lutheran influence in England took two forms. First, the Lutherans were seen as members of an international community of mathematicians offering expert guidance in a highly technical activity. In this respect, Reinhold, Rheticus, Peucer, and Maestlin are no different than Mercator, Cortés, or Gemma Frisius. Religion enters into the story only accidentally. Melanchthon stressed mathematics in the Wittenberg curriculum for religious reasons that his immediate followers adopted, but when their works are cited or otherwise used by English authors, the religious motivations have been erased and only the mathematical content remains. Feild's ephemeris and the translations of Hill and Blundeville fall into this category. For example, Feild based his calculations on Reinhold's *Prutenic Tables*, which would not have existed had Melanchthon not encouraged Reinhold and Rheticus to study astronomy, but Feild is interested in Reinhold as a way of accessing Copernican astronomy.

Second, in a minority of cases we find evidence that English mathematicians were directly influenced by Melanchthon's providential interpretation of astronomy. I suggest that these cases be regarded as mathematical Philippists, with Thomas Digges as the primary example. Hooykaas, who has argued at length for a positive interaction between science and Reformed (Calvinist) theology in the Reformation, has concluded that Digges was probably a Puritan, while noting that Puritanism in Elizabethan England was less theologically distinct than it would become in the seventeenth century. As evidence he points to Digges' association with Robert Dudley, a supporter of Calvinists in the Dutch Republic and of Puritans in England; to his son Dudley, a Puritan supporter like his namesake; and to his cousin Thomas, who had Puritan tendencies.[75]

Following the identification of Digges as a possible Puritan, Hooykaas proceeds to draw comparisons between his scientific activity and Reformed theology. He identifies three motivations for scientific study in the *Alae* and the *Stratioticos*--enjoyment, the glorification of God, and utility--all compatible with Calvin's thought. Yet one of his most prominent religious statements is a direct quotation from Melanchthon, for whom glorification of God and usefulness to human affairs were the cornerstones of mathematical study. Other statements in the *Alae* confirm that Digges approved of the Philippist mathematical program. Hooykaas further suggests that Digges could accept Copernicanism because of Calvin's liberal interpretation of scripture, a very slender thread on which to hang any conclusion about confessional interactions with science. Four of the little group of sixteenth-century heliocentrists were mathematicians whose thought has been traced back to Melanchthon. Now Digges can be added to their number, strengthening the correlation between Philippism and physical Copernicanism.

The concept of mathematical Philippism allows us to re-examine interactions between theology and science in early modern Europe. Distancing attitudes toward nature

[75] Hooykaas, "Thomas Digges' Puritanism," *Archives internationales d'histoires des sciences* 8 (1955): 145-59.

from other aspects of belief, the accepted number of sacraments for instance, is especially important in early Puritanism and other cases where confessional lines had not yet been clearly drawn. Impressionistic similarities such as Hooykaas relies on in his analysis of Digges cannot substitute for the clear association of scientist with reformer. As a corollary, we should also not jump to the conclusion that a given figure deviates from representative theologians of his or her confession without good reason.

The influence of Melanchthon is undeniable in the case of Thomas Digges. He quotes from the letter to Grynaeus, the centerpiece of Kusukawa's analysis of Melanchthon, and a second tie to the reformer can be drawn through his father's citation. In the quotation as well as his own comments we see the key planks of the Philippist mathematical platform: the orderliness of celestial motions confirms God's providential creation of the world; conversely, denial of astronomy leads to atheism and the denial of the soul's immortality and other vital matters of faith; furthermore, those who reject astronomy are Epicureans. Two other figures can be identified as mathematical Philippists. Robert Recorde had the opportunity to learn about the providential program from his reading of Reinhold, who describes it in prefaces to his books. While he does not provide much detail, he considers celestial motions to provide an especially clear example of providence and believes that study of astronomy is uniquely incompatible with atheism; both ideas are strongly suggestive of Melanchthon's influence. Leonard Digges leaves no doubt that he agrees in general terms with Melanchthon. He approves of the reformer's dismissal of skeptics of astronomy as Epicureans. He can be placed firmly in the Lutheran camp alongside his son. In the absence of further information, Recorde's status must remain uncertain.

CHAPTER EIGHT

CONCLUSION

Seen from a modern perspective, the Lutheran reform of astronomy and the Tudor rebirth of education have an air of inevitability about them. Once Regiomontanus has drawn out the mathematical power of the *Almagest*, once John Dee or Robert Recorde has shown the amazing things that can be accomplished with the help of mathematics, it is only a matter of reading the books and repeating what they say. To the people in the midst of these movements, they seemed to be fragile affairs, threatened by the untimely death of but one or two gifted individuals. Either approach, in its simplest form, becomes methodologically suspect "great man" history, yet I find myself sympathizing with the viewpoint of the historical actors. Ideas do not thrive on their own, nor do they spread automatically in the presence of favorable socioeconomic factors. At some point, the individual decision to accept, reject, or modify an idea must come into play. In the case of high-level mathematics, sometimes only a very few people are able and willing to make the necessary decisions.

If this dissertation were "great man" history, then Philip Melanchthon would be the great man. I hope that I have conveyed the more subtle message that his promotion of mathematical studies was one among many factors that shaped the history of astronomy. Even in this narrowly focused study I have had occasion to discuss other influences ranging from problems internal to astronomy through humanist ideology to international relations. Some of these influences would have operated in the same way in the absence of a single person. To take a simple example, Copernicus struck upon heliocentrism before the Reformation had even begun. Yet I suspect that Melanchthon's influence on some areas of the history of science has been seriously underrated.

Any good piece of research, if it is to be useful, should change the contours of our knowledge, either by expanding it into some new area or by forcing us to rethink our existing categories. I am concluding my dissertation with an analysis of how well, or poorly, current historiography fares in light of my research. To this end I have selected a group of classic and recent studies in early modern science on the overlapping themes of religion-science interactions and astronomy among the Lutherans and the English. A significant number of such studies include the question "whose religion?" I begin, therefore, with the story of how that question came to be posed.

The thesis of inevitable conflict between science and religion (generally the Christian religion) represented the dominant historical approach of a century ago. The conflict thesis, though it proved to be both popular and influential, depended on bold but poorly researched claims that could not withstand close examination of the primary sources. Scholars began to suspect that religion was not always actively hostile to science and that religious convictions could even interact with science in positive ways; for instance, a Christian might decide to honor God by studying creation. Religious influence on science has not been a simple either/or proposition, however. Within Christianity, theologians have articulated a wide variety of attitudes toward nature that might not only impel people to science, but also shape the way that scientific research is conceived and carried out. Robert Merton included science as a part of a sociological study of the influence of Puritanism on seventeenth-century English society, carried out in the 1930s. Analyzing the religious affiliations of early members of the Royal Society, he found a disproportionately high number of Puritans and suggested that the Calvinist concepts of the "calling" allowed Puritans to identify themselves as having a vocation for scientific research.[1]

Critics of the Merton thesis have questioned whether his loose definition of "Puritan" skewed the results by including figures who probably did not view themselves as such. If a stricter definition is applied, the proportion of Puritans in the Royal Society drops considerably. Also at issue is the difference between correlation and causation. Merton's approach cannot determine whether theology influenced science directly, or whether both Puritanism and scientific activity were connected to some third factor, such as living in cities or enriching oneself with smart investments. Despite such problems, and despite the failure of historians to agree on some aspect of Reformed theology that made it uniquely supportive of science, the general association of science with Calvinist or Protestant theology has proven to be a remarkably resilient concept. Most research on the subject has focused on science in England from the 1640s and later, at the cost of minimizing the importance of work on the Continent and the changes that natural philosophy underwent in the sixteenth and early seventeenth centuries.[2]

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[1] Robert K. Merton, *Science, Technology & Society in Seventeenth Century England* (New York: Howard Fertig, 1970).

[2] For discussion of the Merton thesis and further instances of the attempt to relate early modern science to Calvin and his followers, see the articles in *The Intellectual Revolution of the Seventeenth Century*, ed. Charles Webster, Past and Present Series (London: Routledge & Kegan Paul, 1974); and *Puritanism and the Rise of Modern Science: The Merton Thesis*, ed. I. Bernard Cohen with K. E. Duffin and Stuart Strickland (New Brunswick: Rutgers University Press, 1990).

Hooykaas has made broad claims for the role of Protestantism in the development of modern science. His most ambitious statement appeared in *Religion and the Rise of Modern Science*, in which he argues especially for Calvin's influence on scientists from diverse confessions. Nature as the awe-inspiring creation of the divine takes pride of place in his analysis:

> What strikes one most about the early Protestant scientists is their love for nature, in which they recognize the work of God's hands, and their pleasure in investigating natural phenomena. . . . The Reformed church taught that the duty of glorifying God for all His works should be performed by all the faculties of man, not only by the eyes, but also by the intellect. Calvin expressed the view that those who neglected the study of nature were as guilty as those who, when investigating God's works, forgot the Creator.[3]

Other doctrines important to Protestants but not Catholics included voluntarism, the priesthood of all believers, and the separation of the books of God (the Bible) and nature. Voluntarism, the belief that God willed the world to be as it is rather than creating by necessity, forced empirical investigation into nature because the rules of nature could not be determined by speculation. The priesthood of all believers freed early scientists from the authority of specialists in theology. And Calvin's separation of the two books warned Protestants not to look to scripture for teachings about nature.

Even allowing for the moment that Protestantism was more congenial to the rise of modern science than Catholicism, and allowing further that Hooykaas has identified the key elements of Protestant theology, he has neglected either to show that they were unique to Calvinist thought or to connect the scientists he discusses to Calvin's writings. He cites Kepler as an example of the glorification of God through the study of his

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[3] Hooykaas, *Religion and the Rise of Modern Science* (Edinburgh: Scottish Academy Press, 1972), 105-106.

handiwork.[4] To argue convincingly that Calvin, and not Melanchthon or some other theologian, was Kepler's inspiration, he must show two things: first, that no theologian more closely connected to Kepler's background expressed similar ideas; and second, that Kepler was likely to have read a relevant Calvinist work. Yet Hooykaas does neither. Calvin's primacy in *Religion and the Rise of Modern Science* appears to rest entirely on the claim that the crucial theology disseminated from the writings of Calvin alone.

Generalizations are to be expected in a book based on a series of lectures over a very broad topic. More troubling is their appearance in the article on "Thomas Digges' Puritanism," in which Hooykaas draws an artificial distinction between the religious outlooks of Thomas and Leonard Digges. The father made explicit reference to Melanchthon, and so his allegiance cannot be denied. The son, as we have seen, also quoted Melanchthon, but he did not name his source. Hooykaas, seeing the passage extolling the heavens as evidence of God's hand in nature, promptly identifies it as Calvinist in tone, then draws a further conclusion about the relative openness of each theologian's methodology to the novel cosmology. Leonard Digges was a geocentrist and a follower of Melanchthon, who quoted scripture to disprove terrestrial motion. But Thomas Digges was a heliocentrist and Calvin did not insist on a literal reading of scripture as a source for natural philosophy. Astrology provides further tenuous support. Melanchthon and Leonard Digges both believed in astrology, while Calvin attacked it and Thomas Digges wrote nothing on the subject. The backward nature of astrology is left unstated but probably to be understood. If Hooykaas' study of Digges is typical of his approach--and at this point I see no reason to think otherwise--then his identification of

[4] Hooykaas, *Religion and Modern Science*, 105.

profound Calvinist influence on early modern science rests on assertion and little more.

Recently Peter Harrison published a new account of Protestant influence on early modern science in *The Bible, Protestantism, and the Rise of Natural Science*, in which the key is found in a shift in biblical hermeneutics during the Reformation. Augustine formalized a set of four exegetical approaches to the Bible: historical, allegorical, analogical, and anagogical. The *historical* or *grammatical* interpretation looks for the literal sense of the Bible; Jerusalem, for instance, is a Jewish city. The *allegorical* interpretation sees in the past an anticipation of future events; Jerusalem in the Bible represents the Church. The *analogical* or *tropological* interpretation finds moral guidance in the Bible; prophets praising the people of Jerusalem or rebuking their ungodly behavior represent the praise or rebuke of the soul. And the *anagogical* interpretation shows from the Bible what is to be hoped for in the future life; Jerusalem is the heavenly city. Where the Bible mentions objects from nature, these too became subject to hermeneutics, until Christians became accustomed to reading all of nature for its allegorical and moral lessons.

Luther and other Protestant theologians rejected all but the historical interpretation and insisted that the Bible be read for its literal sense alone. In doing so, they also removed the allegorical, analogical, and anagogical interpretations of nature. Protestant scientists could no longer view the world as a series of moral examples; they had to confront natural phenomena as nothing other than what they were. Harrison uses the pelican as an example of the process. Medieval bestiaries from the *Physiologus* onward recount how the pelican kills its young and mourns over them for three days. Then, pecking itself in the side, it sheds its own blood on the chicks and so brings them back to life. The medieval pelican is an obvious symbol of Christ's passion. Protestants rejected the medieval story and concentrated on describing the observable characteristics of the bird in texts somewhat resembling modern ornithological studies. Fabulous beasts provide another example. For medieval Catholics, creatures like unicorns were important for their moral lessons but Protestants worried whether unicorns existed or were the product of imagination or misidentification.

One might wish that Harrison had done more to exclude other factors. He does a good job comparing parallel subjects in medieval Catholic and early modern Protestant texts, but does much less with the works of Reformation-era Catholics. A similar charge might be leveled against Hooykaas and some other scholars who have argued for the greater contribution of Protestant theology to changes in science during the early modern period. In Harrison's case, a partial remedy might be to show that bestiaries, emblem texts, or other moralizing genres continued in popularity among Catholics after they had gone out of vogue in Protestant circles. On the other hand, if the move away from allegorical readings of nature progressed at about the same rate among Catholics and Protestants, it becomes hard to agree that Protestant hermeneutics caused the rise of modern science instead of humanism or another shared factor.

Harrison is at his most convincing when he talks about the life sciences or natural history, where the moralization of nature is common and the dependence on biblical hermeneutics is obvious. Yet he maintains that his thesis applies to physical and mathematical sciences as well:

> [T]he study of the natural world was liberated from the specifically religious concern of biblical interpretation, and the sphere of nature was opened up to new ordering principles. The mathematical and taxonomic categories imposed by Galileo and Ray on physical objects and living things represent an attempt to

reconfigure a natural world which had been evacuated of order and meaning.[5] As an aside, I shall note that Galileo may not be the most felicitous example in an argument for the influence of Protestant theology upon science. But the main point at issue is whether "order and meaning" were indeed stripped away from mathematics and physics by the reform of biblical hermeneutics.

The history of medieval and Renaissance astronomy, some of which has been sketched in this dissertation, shows little if any direct impact from shifting exegetical methods, but Harrison's episodic approach obscures dramatic developments in the period immediately prior to the Reformation. One of his episodes is the twelfth century, which means figures like Hildegard of Bingen whose astrological writings posited an analogy between the macrocosm of the heavens and the microcosm of the human body.[6] But from the twelfth century Harrison passes straight to the sixteenth; the first astronomer whom he discusses in any detail is Galileo. In the intervening four centuries, Europeans rediscovered the powerful astronomy of the Greeks, then had their potential understanding of that astronomy greatly advanced by Peurbach and Regiomontanus. And Greek astronomy has always been written in the language of mathematics, not the language of allegory. The medieval *sphaera* and *theorica* genres and the *Epitome of the Almagest* read the world only in the literal sense.

Harrison spells out a connection between hermeneutics and heliocentrism only toward the end of the book:

> Belief that the earth lay immobile at the centre of the cosmos was not, in the sixteenth century, merely a matter of giving assent to a geocentric theory of the

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[5] Harrison, *The Bible, Protestantism, and the Rise of Natural Science* (Cambridge: Cambridge University Press, 1998), 4.

[6] For Hildegard, see Harrison, *Bible and Natural Science*, 53-54.

> solar system. It was linked to a set of commitments of metaphysical, moral, religious, and anthropological import, not least of which was to do with the dignity of human beings and their place. . . .[7]

But Melanchthon increased the allegorical content of the heavens. The stars are connected to us through their astrological influences, they benefit us materially by providing a calendar as the basis for ordered society, and above all, through their very predictability they manifest divine providence and teach the immortality of the soul. In the preface to Sacrobosco's *Sphaera* he wrote that

> . . . it seems to me indeed that the eyes themselves have the greatest affinity with the stars. Just as the sun shines in the world, so in man, too--whom some call a "small universe" (*mikron kosmon*) because of several similarities--his own lights or stars are created. Therefore those who disdain these related lights do not contemplate the work of nature, and for that reason they deserve to have their eyes plucked out, since they do not want to use them for the purpose for which they are chiefly made. . . .[8]

Melanchthon found powerful moral and allegorical lessons in the heavens, and inspired early Copernicans to do the same. Objections can also be found in medieval physics, where scholastic texts seldom refer to God or religious matters, and Renaissance geography, where Ptolemaic geography began pushing out the older *mappaemundi* in the fifteenth century.[9] Harrison has produced a compelling account for the life sciences and natural history but overextended it in an attempt to encompass all sciences.

A small number of studies of science and religion in the Reformation have attempted to identify different theological trends within a religious confession, as opposed to comparing Protestantism with Catholicism. This was not always the case.

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[7] Harrison, *Bible and Natural Science*, 268.

[8] Melanchthon, *Orations*, 106 (Salazar's translation).

[9] On religion in scholastic physics, see Grant, *God and Reason in the Middle Ages* (Cambridge: Cambridge University Press, 2001), especially 186ff.

Paul Kocher's *Science and Religion in Elizabethan England*, a dated but still useful survey of a neglected subject, began by comparing the pronouncements of Luther and Calvin on religion, concluding that "it was lucky for Elizabethan scientists that the prevailing climate of theology in which they worked had been set by Calvin."[10] The examples in this dissertation suggest that Calvinist influence on Tudor science may be considerably less than once thought. Melanchthon is an especially promising figure for studies of religion and science because in him we find a theologian who wrote at length about natural philosophy and who has indisputable connections to his students at Wittenberg.

Thus far, the most extended treatment of Melanchthon as a scientific figure has been Sachiko Kusukawa's *The Transformation of Natural Philosophy: The Case of Philip Melanchthon*. I shall not repeat her arguments here, since they have already been presented in chapter 2. My references to her analysis throughout this dissertation show that I have found her account of Melanchthon to be convincing as well as conducive to further research. Every text I have examined in which Melanchthon writes about the heavens repeats some version of arguments in his *Sphaera* preface. As Kusukawa herself points out, her contextualization of Melanchthon as a classicist surrounded by civic disturbance provides a new dimension to the history of science and religion.

> This is precisely why, I believe, traditional accounts of "Protestantism and science" which have concentrated on an internal analysis of Protestant theology have been unfruitful. Logical compatibility between reading the Bible and making "scientific" claims about the physical universe cannot explain sufficiently why a particular type of natural philosophy, with its peculiar readings of Vesalius and Copernicus, was needed at all for Lutherans.[11]

[10] Kocher, *Science and Religion*, 10.

[11] Kusukawa, *Transformation of Natural Philosophy*, 203-204.

As she proceeds to observe, Calvin, who is so often quoted as providing a religious motivation for science, did nothing himself to create or promote a natural philosophical program.

Kusukawa's main weakness is inadequate treatment of the content of scientific ideas. Given that she treats certain aspects of Melanchthon's thought in considerable detail, neglect of others is understandable, but it leads to an unsatisfactory account of the reception of Copernicus at Wittenberg. Reinhold and Rheticus barely appear in the book, yet to the degree that Melanchthon understood and adopted Copernican astronomy, he undoubtedly did so with the assistance of his protégés. Kusukawa concludes that "Copernicus was important for Melanchthon because of his contribution to natural philosophical astrology. Copernicus' calculative improvements implied better accuracy in predicting planetary positions, a crucial point for astrology."[12] Such an interpretation seems to be contradicted by Melanchthon's own statements to the effect that the providential testimony of astronomy matters even more than the application of predictions in astrology. In his own words, "What more truly is fitting to prophets than to confirm true and pious opinions about God in men's spirits?"[13] Another manifestation of this impulse is Reinhold's praise for the abolition of the equant, a change which offered no predictive improvements but provided better information about the arrangement of the celestial realm.

I believe that Kusukawa's de-emphasizing of astronomy as a science in its own

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[12] Kusukawa, *Transformation of Natural Philosophy*, 172-73.

[13] Melanchthon, from the preface to Sacrobosco, *Computus*, translated in appendix 1.

right stems from her legitimate attempt to capture the blurring of Aristotelian categories in Melanchthon's natural philosophy. Despite the wide separation given astronomy and astrology in the traditional university curriculum, Melanchthon included both in his physics textbook *Initia doctrinae physicae*. At the same time he continued to draw a fine line between motions and effects.

Jesse Kraai's dissertation on "Rheticus' Heliocentric Providence" incorporates Kusukawa's work on the role of astrology in Melanchthon's thought into a study of his most famous mathematical student. I have noted some of Kraai's errors in chapters 2 and 4, including his misrepresentation of Melanchthon as an astrological fatalist, his confusion of different elements in the Copernican account of terrestrial motion, and his implausible interpretation of the giants metaphor in Melanchthon's 1542 letter to Camerarius. It should be noted that there is material here of value to the serious scholar. Kraai has done much work to untangle Rheticus' complicated itinerary in the crucial period between 1539 and 1543. He has also provided welcome contextualization by identifying Rheticus' possible associates at Wittenberg and by approaching the students as humanists engaged in a variety of activities, including the writing of poetry, rather than as pure mathematicians. His research on the Prophecy of Elijah and the study of history at Wittenberg brought the *Chronicle Carionis* to my attention and deepened my appreciation of the "Monarchies" passage in the *Narratio prima*. However, I cannot agree with his overarching conclusions about Rheticus.

Kraai places astrology front and center in his analysis of Rheticus; in fact, he regards it as a pivotal issue in the history of the Lutheran movement as a whole. Contrasting Melanchthon's attitude toward astrology with Luther's suspicion of the art, he writes that “The issue was central to the anti-Melanchthon backlash which began toward the end of his life” and identifies it as a major issue in the split between Philippists and Gnesio-Lutherans.[14] In contrast to Kusukawa’s nuanced discussion of the relationship between astrology and astronomy, Kraai believes that Melanchthon came to equate the two, possibly at Rheticus’ instigation, in the preface to the *Computus* when he calls astronomy *mantike*, and that the same equation appears in the *Oration on Astronomy and Geography*.[15] In reality the two documents call both astrology and astronomy forms of divination, the one because it reveals the weather and the other because it reveals the existence of God.

Kraai constructs a new category of “mathematical realism” to describe Rheticus’ attitude towards heliocentrism. According to Kraai, Melanchthon faced the problem of converting astrology from its polytheistic roots, in which celestial influences emanated from the struggles between planetary gods, to true monotheism with all influences emanating from a single omnipotent God.

> This was the impetus behind Melanchthon’s drive toward a new mathematization of astrology. Indeed, astrology had always needed math, but only for the purpose of calculating planetary positions. This new mathematization was based on the profound idea that if the planets no longer had wills of their own and no longer moved of their own accord, but were rather moved by God, only a mathematical scheme *underlying* the rhythms of the planetary motions could account for God’s necessary Providence.[16]

Rheticus found the desired underlying scheme in Copernican astronomy. For him, “the Copernican circles are ‘theologically real,’ they determine worldly events and are ambassadors of God’s omnipotence and His desire to be known by man,” but their

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[14] Kraai, “Rheticus’ Heliocentric Providence,” 10 and n. 17.

[15] Kraai, “Rheticus’ Heliocentric Providence,” 88-90.

physical reality is of no interest.[17]

Kraai's conclusion require a series of unlikely suppositions. First, if Kraai is correct, then both ancient and medieval astrologers must have assumed that planets wandered about arbitrarily, and Melanchthon and Rheticus were unprecedented in their belief that authentic mathematical harmonies underlay the motions of the planets. This is simply absurd. The planets moved about freely in the ancient philosophy of Stoicism, but in both Platonism and Aristotelianism, the planets were carried by aetherial orbs. In the later Middle Ages and the Renaissance, the dominant natural philosophies were Aristotelian and Platonic. Furthermore, the dominant trend in Aristotelian physics immediately prior to the Reformation agreed with Ptolemaic astronomy in many points, while Averroism was in the minority. Inquiries into the nature of celestial orbs, for instance, often concluded by accepting eccentric orbs and epicycles as physically real.[18] According to Kraai, however, astrologers must have consistently ignored physical doctrine.

Second, if Kraai is correct, then geocentrism is somehow inconsistent with monotheism. He argues that Melanchthon perceived existing astronomy to be unsatisfactory even before Rheticus learned about Copernican astronomy. Unfortunately, Kraai does not spell out the conflict between monotheism and Ptolemaic mathematical models, but it appears to be based on a contrast between medieval polytheistic astrology and the unity of Copernican astronomy, which links diverse phenomena to the Sun through a "golden chain," as explained by Rheticus. I have already argued against Kraai's

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[16] Kraai, "Rheticus' Heliocentric Providence," 144.

[17] Kraai, "Rheticus' Heliocentric Providence," 147.

picture of fifteenth-century astrology predicated on warring gods moving arbitrarily through the heavens. If such a picture never existed in the first place, then no sudden conflict with monotheism could have arisen from its abolition. Melanchthon himself apparently never felt a conflict; his call for the reform of astronomy, which I believe to be the source of Kraai's confusion, was motivated by the practical problem of completely recovering and understanding the astronomy of the ancients.

Third, if Kraai is correct, then much of the *Narratio* itself is meaningless. He claims that Rheticus considered the Copernican models to be "theologically real" but did not care whether they were physically real. Yet the passage expounding on the advantages of heliocentrism in the *Narratio* (translated in appendix 4) discusses the consequences of physical models. Rheticus' concern with the parallax of Mars only makes sense if he thinks of *De revolutionibus* as a statement about the actual arrangement of the heavens. It requires that the relative distances of Mars and the Sun change in ways that can be observed on Earth. Likewise, the preservation of circular motion was introduced as a solution to the physical problem of reconciling equant motion with the principle of uniformity in celestial motion. Kraai identifies Rheticus as a "mathematical realist," a category with only one representative, by ignoring Rheticus' clearest statement of the advantages of heliocentrism.

A second recent dissertation on early modern astronomy has been published as *Luminaries in the Natural World: The Sun and the Moon in England, 1400-1720* by Anna Marie E. Roos. The author's area of expertise lies in seventeenth-century scientific popularizations, and where she restricts herself to her accustomed subject matter, she has

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[18] Grant, *Planets, Stars, Orbs*.

provided fascinating glimpses of concepts of the Sun and the Moon in early modern England. However, she has superimposed on her material an ambitious thesis of "desacralization." The term comes from the work of M.-D. Chenu, who identified a changing attitude toward nature in the twelfth century. Where they had once been content to appeal directly to the omnipotence of God, scholars began to look into the secondary causes restraining natural phenomena.

> This desacralizing of nature--and of the outlook men brought to nature--produced an unmistakable crisis both in the recourse to symbolist interpretation which a certain way of looking at nature invited, and in the limitations now placed upon the preternatural.[19]

Roos adopts Chenu's concept but argues that "Chenu does not account for the continuous sacrality of the heavens that was in fact strengthened by the preservation of their incorruptibility by 'high scholastics' like Aquinas."[20] One of her major examples of desacralization is the speculation that planets might be Earthlike worlds.

According to Roos, the "sacrality of the heavens" manifested itself in the separation of cosmology (treated as interchangeable with physics), mathematical astronomy, and astrology until 1543, when the introduction of Copernicanism to England began to erode disciplinary divisions by turning the Earth into a planet and the planets into other Earths. Characteristics that marked the sacrality of the Sun and Moon "include immutability, circular motion, and the emanation of astrological effects whose ultimate cause was known only to the creator."[21] Cosmology insisted on immutability and

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[19] M.-D. Chenu, *Nature, Man, and Society in the Twelfth Century: Essays on New Theological Perspectives in the Latin West*, transl. Jerome Taylor and Lester K. Little (Chicago: University of Chicago Press, 1968), 14.

[20] Roos, *Luminaries in the Natural World*, 61 n. 138.

[21] Roos, *Luminaries in the Natural World*, 11.

circularity despite lunar spots, the irregularity of planetary motion, and other anomalies; astronomy observed and predicted appearances but did not reproduce the true arrangement of the heavens; and astrology predicted planetary influences on the terrestrial realm without attempting causal accounts. Roos' concept of desacralization is intertwined with a strongly instrumentalist interpretation of astronomy; cosmology could uphold the sacrality of the heavens only so long as astronomy remained subordinate. Once English mathematicians realized that they could make independent statements about cosmology, the luminaries lost their sacred status.

As I have argued at length in this dissertation, subordination does not mean irrelevance. The Ptolemaic tradition allowed mathematicians to provide information about the heavens within the limits set down by philosophers. Physics demanded uniform circular motion, but astronomy specified which possible sets of circular motions applied to each planet. The elaborate calculations of the dimensions of celestial orbs point to a belief in the reality of astronomical models, at least among astronomers. We should question further whether immutability and circular motion truly constitute sacrality. Belief in a radical division between celestial and terrestrial realms did not prevent scholastics from intellectually probing the heavens. Late medieval physics texts show few signs of "the preternatural" or of "symbolist interpretation," even with respect to the heavens; instead they show the influence of logic, the omnipresent tool of the philosophers. Roos fails to convince with her desacralization thesis because she presupposes a state of affairs that never existed. Without preliminary sacrality, the erosion of the cosmological division between celestial and terrestrial must be attributed to other historical factors.

I have discussed Kraai and Roos at length because, despite their problematic conclusions and their occasionally low standards of historical method, they are virtually the only book-length recent studies of religion and astronomy that overlap to any great extent with the subject matter of this dissertation. A third member of this group is *God's Two Books: Copernican Cosmology and Biblical Interpretation in Early Modern Science* by Kenneth Howell. Howell has taken a narrowly-defined topic, the interaction between biblical exegesis and reactions to Copernicus, and applied it to a series of episodes in both Catholic and Protestant regions. Unlike Kraai and Roos, Howell is reasonably well-informed about the relevant historiography and uses it as the starting-point for his own analysis. The result is a book summarizing the current state of thought about religious dimensions of Copernicanism and early modern astronomy.

Howell's book is especially strong in the scope of its treatment. Besides the obvious selections of Melanchthon and Rheticus, Galileo and Kepler, he includes obscure figures such as Fracastoro and Peucer and events such as the debate over Copernicanism in the seventeenth-century Dutch Republic. He approaches each figure as potentially unique. Instead of beginning with a theologian representative of a confession, such as Luther or Calvin, and proceeding to apply that theologian's attitudes toward nature to all scientists who are members of the confession, Howell looks for clues about an author's biblical exegesis within his own writings and is prepared even to find differences where there is a known link between astronomer and theologian, as happens in three chapters on Melanchthon and his followers. Individualized treatment of the sort offered by Howell is a necessary corrective to the generalizations of an earlier generation, exemplified by Hooykaas, that fail to withstand close examination.

Howell has approached his subject from the perspective of religious history, not history of science. Because of his unfamiliarity with early modern astronomy, he fails to recognize the context of his primary sources and sometimes draws unlikely conclusions. One example is his analysis of an early oration given by Tycho Brahe in 1574.[22] The oration repeats a story from Josephus' *Jewish Antiquities* that Adam taught astronomy to his son Seth, who passed it on to Abraham and thence to the Egyptians. The patriarchal origins of astronomy serve to legitimize astrological studies. Howell regards Brahe's use of the story as surprising, relates it to his hermetic sympathies, and identifies his friend Peter Severinus as the likely source of the argument. In reality, the story was well-known. It appears in Caxton's *Myrrour of the World* and lies behind Melanchthon's assertion in the *Computus* preface that God inspired the "first parents" to study astronomy. Brahe probably learned the story from Peucer, who was briefly his teacher. Peucer included in his *sphaera* a chronology of astrologers stretching from Adam and Seth to Copernicus and Reinhold. Far from being a novelty, Brahe's oration appears as a typical specimen of Philippist mathematical rhetoric.

Howell combines the two main historiographical branches of this dissertation, making his book a suitable point to shift from the theme of science and religion to the history of astronomy. I will not attempt to summarize the most technical studies here. I could do little more than agree with their expositions of the astronomical models; my debt to them should be apparent in the notes to chapters 2 and 3. In creating a narrative structure to connect the authors central to this dissertation, I have relied most heavily on the work of Robert S. Westman, above all his article "The Melanchthon Circle, Rheticus,

[22] Howell, *God's Two Books*, 78-83.

and the Wittenberg Interpretation of the Copernican Theory," for the Lutherans; and for the English, Francis R. Johnson's *Astronomical Thought in Renaissance England: A Study of the English Scientific Writings from 1500 to 1645*.

I shall begin with Johnson's book, as it is by far the older work (first published in 1937, whereas Westman's article appeared in 1975). The author writes that his goal is "to chart the course of astronomical thought in scientific circles during that significant period of transition from the old cosmology to the new. It will therefore present the results of a first exploration in territory hitherto almost wholly uncharted."[23] Johnson uncovered a wealth of information about forgotten, or nearly forgotten English authors; he was, for instance, one of the first in modern times to observe that Bruno's Copernican vision of an infinite universe was anticipated and possibly even inspired by Thomas Digges.[24] Outside the minor astrological works and prognostications of the English Renaissance, which are too numerous to catalogue in any but the most specialized studies, it is difficult to find an English astronomical work that does not receive at least a brief description by Johnson. In many instances the scientific figures he discusses have received little or no attention from later historians.

If *Astronomical Thought in Renaissance England* has a shortcoming, it is the author's Whig approach to the study of Copernicanism, which sometimes is limited to a positivist checklist of works opposing or conducive to the idea of terrestrial motion. Eschewing all mention of heliocentrism in sixteenth-century astronomy would be counterproductive. However, a book-length treatment should not only attempt to

[23] Johnson, *Astronomical Thought*, vii.

[24] Johnson and Larkey, "Thomas Digges."

understand the impact of *De revolutionibus* in terms familiar to its contemporaries, but also recognize other factors at work. Johnson creates a rough periodization dividing pre-Copernican and post-Copernican astronomy in England, with the line drawn around 1550 when copies of *De revolutionibus* may have been reaching the island. I suggest that he has located the transition at the right time, but for the wrong reasons. A crucial change, as I have argued in chapter 6, is not the importation of a new cosmology but the imitation of foreign educational practices. Robert Recorde involved himself heavily in the transition by writing a series of mathematical textbooks similar to the sequence followed at continental universities. His comments on terrestrial motion were interesting in retrospect, but only a fortuitous coincidence.

Johnson deliberately follows an internalist approach, tracing influences within the scientific community but setting aside connections to literature, philosophy, and other external factors. I suggest that the English entry into the Age of Exploration partially explains the rebirth of mathematics. Around mid-century the death of Henry VIII paved the way for a series of expansionist governments, creating among wealthy and powerful patrons a demand for works of cosmography and navigation. The 1540s and 1550s saw not only the publication of *De revolutionibus* and Recorde's *Castle of Knowledge*, but also Sebastian Cabot's return to England, Richard Eden's first cosmographical translations, and the start of John Dee's career as a teacher of pilots. These four English figures would have been largely unaffected by Copernicus' absence.

For my purposes, Westman's article on the "Melanchthon Circle" defines the Lutheran astronomers in much the same way as Johnson's *Astronomical Thought* defines the English mathematical practitioners. Each work examines the reaction to Copernicus among the major figures of an educational movement. Westman defines the reaction among Melanchthon's followers as the "Wittenberg Interpretation of Copernicus":

> By and large, the principle tenet of the Wittenberg viewpoint was that the new theory could only be trusted within the domain where it made predictions about the angular position of a planet. . . . Beyond this basic attitude, some members of the Wittenberg circle believed that certain Copernican models--such as those which replaced the Ptolemaic equant with epicyclic devices--were to be preferred. An important plank of the Wittenberg program . . . was the goal of translating those equantless devices into a geostatic reference frame.[25]

Westman is correct to single out eradication of the objectionable equant as a defining characteristic of astronomy at Wittenberg. At the same time, he recognizes that other elements of Copernican astronomy caught the attention of Reinhold and other mathematicians. Currently, however, we lack information about how those other elements contributed to the reception of Copernicus at Wittenberg or elsewhere; only the equant has been the subject of systematic historical study. We cannot say whether all groups received the different elements of Copernican astronomy with equal enthusiasm, for example. Westman may even have inadvertently contributed to the oversight by drawing attention to the equant.

I have attempted a start toward remedying this deficiency by scrutinizing the adoption of Copernican ideas, or even their positive mention. The tradition of cosmic measurements appears to have been popular among Lutheran astronomers, who frequently drew on *De revolutionibus* in connection with the sizes and distances of Sun and Moon. Possibly their interest was in correcting lunar parallaxes for predicting eclipses, though at this point my suggestion is purely speculative. But among the English, this avenue proved to be less productive; instead, they shared with the Lutherans an

[25] Westman, "Melanchthon Circle," 166-68.

enthusiasm for the new trepidation model. The librations constitute virtually the only Copernican model that is relevant to the *sphaera* genre, because both precession of the equinoxes and the changing obliquity of the ecliptic affect the celestial circles. Throughout the Tudor period, *sphaeras* and their equivalent (including navigational textbooks) dominated astronomical publications. No *theorica* was printed in England before Blundeville's in 1602.

My agreement with the Wittenberg Interpretation of Copernicus as an analytical category should be clear from my reliance on Westman's research in chapters 4 and 5. I suggest, however, that we view the reactions of Wittenberg astronomers to Copernicus as part of a general Wittenberg interpretation of astronomy that critiqued not only heliocentrism but all astronomical claims without demonstrable certainty. Kusukawa's work on the providential program of Melanchthon has revealed why a small group of mathematical practitioners began to concern themselves with discovering the true arrangement of the heavens as an end in itself. They had access to the power of mathematical demonstration, which, as Rheticus observed, provides not only certainty but the feeling of certainty. Where proof was not possible, however, they had to acknowledge the limitations of their field and seek answers in other disciplines, above all in physics. Astronomy alone could not decide whether the Sun moved or the Earth, or whether a given astronomical model was to be explained by eccentric or epicycle. Certain observations suggested the Earth's centrality--for instance, the equal division of the sky by the horizon--but these could not stand against the Copernican dictum that the Great Orb of the Earth, not just the Earth itself, was inconsequentially tiny. Thus Peucer resorted to physical and scriptural rebuttals of Copernicus, taken from Melanchthon's physics textbook, in his mathematical *sphaera*.

Because the Wittenberg astronomers and their successors wanted to know more than just the angular positions of celestial objects, they took care to indicate the limitations of mathematical knowledge whenever appropriate. Reinhold subjected Peurbach to an implicit critique when, in the 1553 revision of the *Theoricae novae*, he presented the interchangeability of the eccentric model and the epicycle-on-concentric. Maestlin took a similar approach when reprinting the *Narratio prima*, where he observed that Copernicus had chosen a double eccentric model for some planets, an epicycle-on-eccentric for others, and an epicycle-on-epicycle for the lunar model. Yet the three combinations were interchangeable and Copernicus' choices were not certain. This reserve is all the more noteworthy when we consider Maestlin's commitment to the power of mathematics, which he deployed to confirm heliocentrism in his treatise on the comet of 1577.

Westman made a second contribution to the history of astronomy in his article "The Astronomer's Role in the Sixteenth Century." The article shows that early resistance to Copernicus arose in part from disciplinary boundaries: physics was entitled to make cosmological pronouncements, but the subordinate discipline of mathematics was not. In a famous footnote Westman lists ten figures whom he accepts as serious followers of Copernicus before 1600; he considers evidence for other candidates to be either too scanty or too inconclusive for determining their cosmology.[26] Although one or two individuals might be added, Westman's list and its assessment of the sixteenth

[26] Westman, "Astronomer's Role," 136 n. 6. For a re-assessment of the list see Tredwell and Barker, "Copernicus' First Friends," which explores the motivations for each figure's conversion to Copernicanism. The latter article is the basis for some of my conclusions here.

century has been generally accepted. A tiny handful of people found something in the new astronomy to persuade them to abandon the cosmological norms of their culture. A few others--like John Feild, the author of the English Copernican ephemeris--may have agreed with Copernicus but never wrote quite enough for us to be certain. The vast majority either kept quiet about the Earth's motion or attacked it openly.

Who made it onto Westman's short list? Four were German mathematicians, trained in Lutheran universities, products of Melanchthon's educational reform: Georg Joachim Rheticus, Christopher Rothmann, Michael Maestlin, and Johannes Kepler. Of the remainder, five fit no clear pattern. Simon Stevin, the first Dutch Copernican, remained secretive about his religious affiliations. Diego de Zuñiga, a Catholic theologian from Spain, introduced Copernicus to support a literal interpretation of Job 9:6 (in which God "shaketh the earth from her place"). Galileo Galilei, another Catholic, publicized his Copernicanism only after his telescopic discoveries began in 1609. His main interest in heliocentrism appears to have been as an alternative to Aristotelian natural philosophy, and his preferred arguments for the Earth's motion were physical, not mathematical. His countryman Giordano Bruno held an eccentric set of religious ideas that led to his execution for heresy. Bruno did not understand the mathematical advantages of Copernicanism and expounded idiosyncratic astronomical models that disallowed bounded elongation of the inferior planets as well as phases of the Moon. Thomas Harriot, an English mathematician, earned a place on Westman's list through obscure manuscript evidence.

The tenth Copernican is Thomas Digges, who can now be given an honorary place with the Germans as a mathematical Philippist, by inclination if not by formal university education. In other words, fully half of the earliest Copernicans, regardless of what their official confession may have been, followed a distinct theological tradition that looked for evidence of God in mathematics. Even though Melanchthon himself was neither mathematician nor Copernican, his respect for the power of the arts curriculum fostered a remarkable correlation of religious outlook and scientific novelty.


res, quædam minores ſecundum qoud plus acce-
dunt uel recedunt a firmamento. Vnde inter illas
ſpheras, ſphera ſaturni maxima, ſphera uero lu-
næ minima, pro ut in ſequenti figura continentur.

B ij Secundū

1. Ptolemaic cosmological diagram showing spheres in cross-section. At the center are the elementary spheres of earth and water combined, air, and fire. Beyond are the celestial spheres, from the realm of fire outward: Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, fixed stars, ninth sphere with zodiacal signs (causing precession) and tenth sphere with stylized zodiacal images (causing daily motion). From Sacrobosco, *Liber Iohannis de Sacro Busto, de Sphera* (Wittenberg: Iosephus Clug, 1534), fol. B2r.

Figure 2: Armillary sphere representing the cosmos in miniature. The vertical rod is the axis of daily motion. The middle horizontal circle is the equinoctial. The broad band crossing the equinoctial at an angle is the zodiac; the ecliptic runs along the center of the zodiacal band. The Tropics of Cancer and Capricorn are the horizontal circles touching the upper and lower extremes of the zodiac From Sacrobosco, *Sphaera mundi compendium foeliciter inchoat* (Venice: Iacobus Pemtius de Leucho, 1519), fol. 3v.

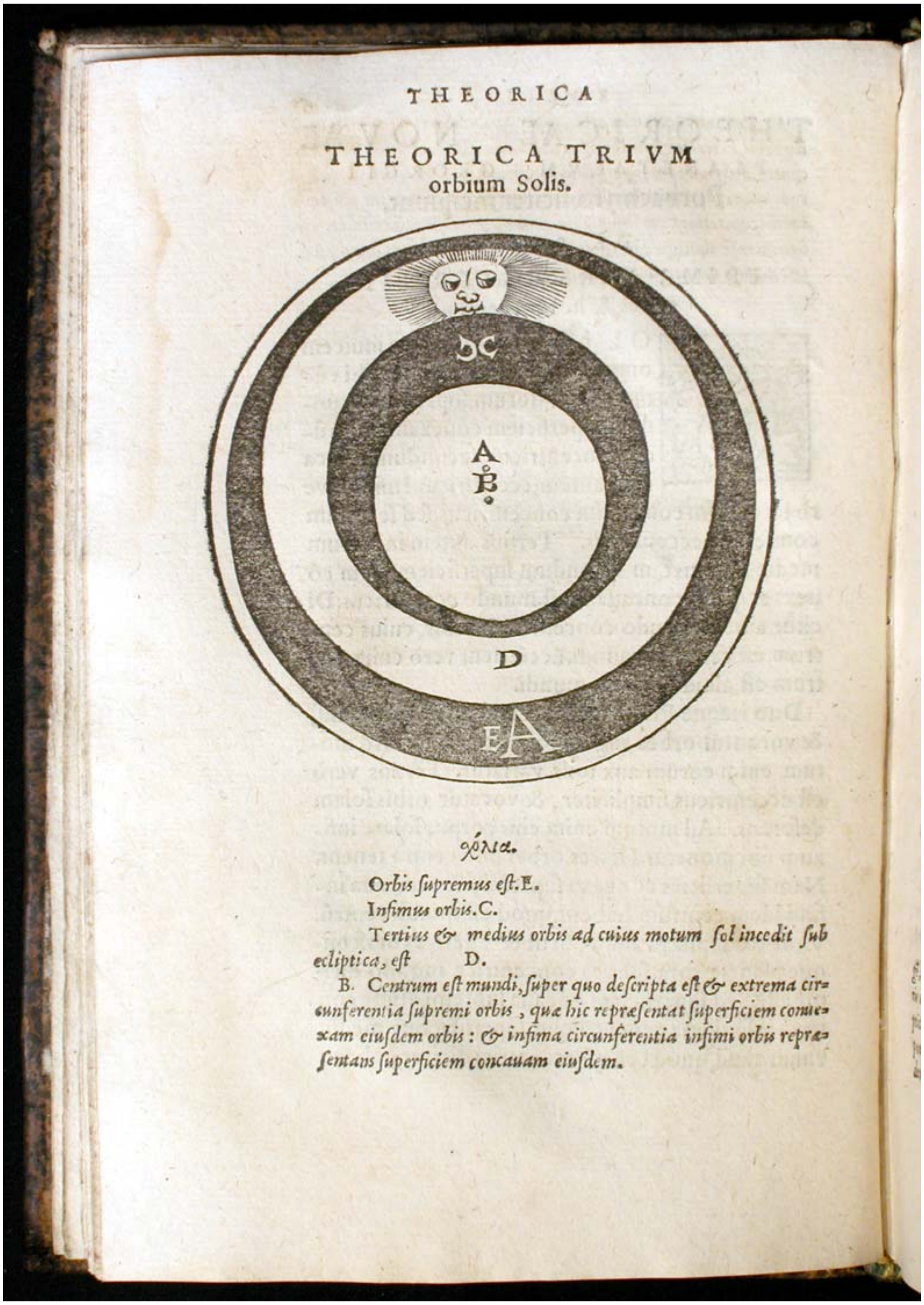

Figure 3: Ptolemaic solar model represented as orbs in cross-section with Sun at apogee. B is the Earth. The central A is the center of the eccentric orb D, which is the solar deferent. The black orbs carry the solar apogee and keep the system as a whole homocentric with the Earth. From Peurbach, *Theoricae novae planetarum Purbacchii Germani ab Erasmo Reinholdo Salveldensi pluribus figuris aucta* (Paris: Carolus Perier, 1553), fol. 6v.

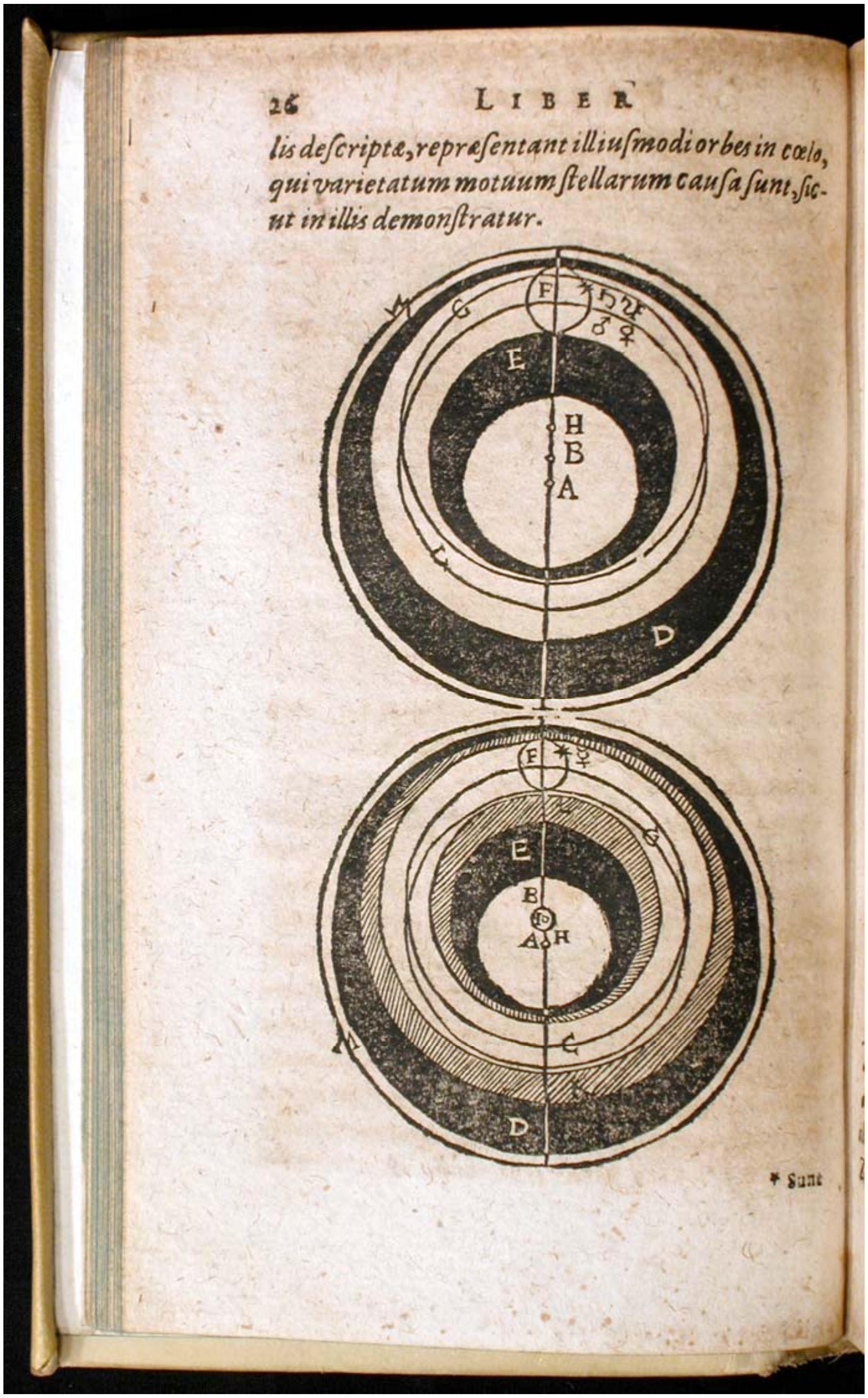

Figure 4: Ptolemaic planetary models. Top: the superior planets and Venus. The Earth is at A, the eccenter at B, the equant point at H. The epicycle is carried by the white eccentric orb, but the center of the epicycle F moves uniformly with respect to the equant, not the geometric center of its motion. Bottom: Ptolemy's Mercury model. From Maestlin, *Epitome astronomiae* (Tübingen: Philippus Gruppenbachius, Impensis Ioannis Berneri, 1610), 26.

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rum horizontis & æquinoctialis, alia est sphæra recta, alia obliqua, alia parallela.

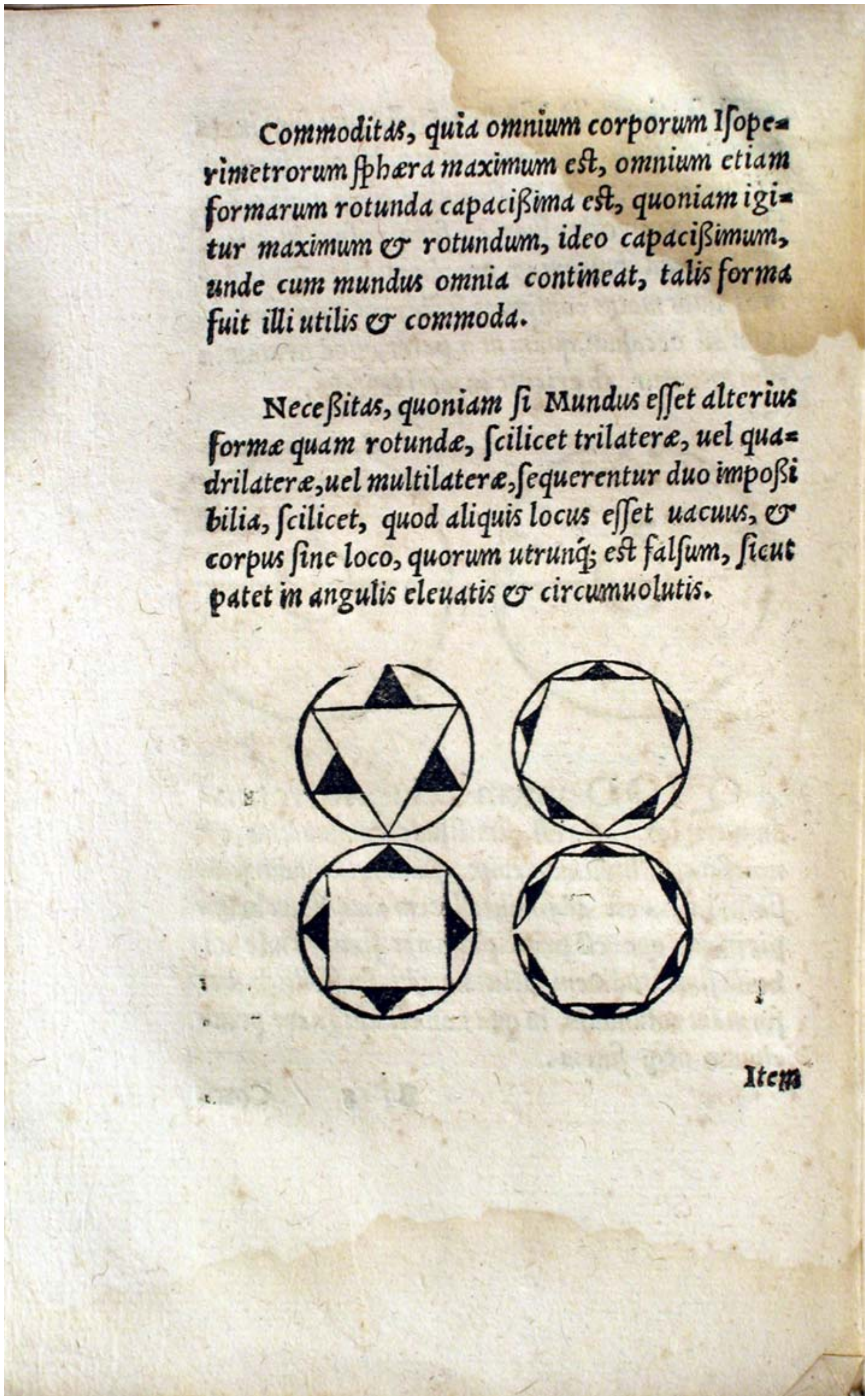
* Quid est Sphæra recta?

Est talis positio sphæræ, in qua horizon & æquinoctialis sese secant ad angulos rectos.] Vel, Est talis positio sphæræ, in qua axis sphæræ incumbit plano horizõtis. Siue. In qua uterq; polus sphæræ est in horizonte. Recta dicitur ab angulis rectis horum circulorum. Transit autem uterq; circulus per alterius polos, unde qui sub æquatore degunt sphæram rectam inhabitant.

* Quid est Sphæra obliqua?

Est talis positio sphæræ, in qua horizon & æquinoctialis sese secant ad angulos obliquos.] Vel. Est talis positio sphæræ, in qua axis sphæræ ab horizontis plano obliquè secatur. Siue. In qua alter polorum sphæræ eleuatur) non tamen perpendiculariter) supra horizontẽ, alter infra eundem deprimitur. Obliqua dicitur ab angulis obliquis horũ circulorum, Declinat autem uterq; circulus

Figure 5: *Sphaera recta* and *sphaera obliqua*. At *sphaera recta* (top) an observer at the Earth's equator sees the equinoctial, passing directly overhead, form a right angle with the horizon. At *sphaera obliqua* (bottom) an observer at some point not on the equator sees the equinoctial form an oblique angle with the horizon. The elevation of the pole is equal to the observer's terrestrial latitude. From Maestlin, *Epitome astronomiae* (Tübingen: Philippus Gruppenbachius, Impensis Ioannis Berneri, 1610), 32.

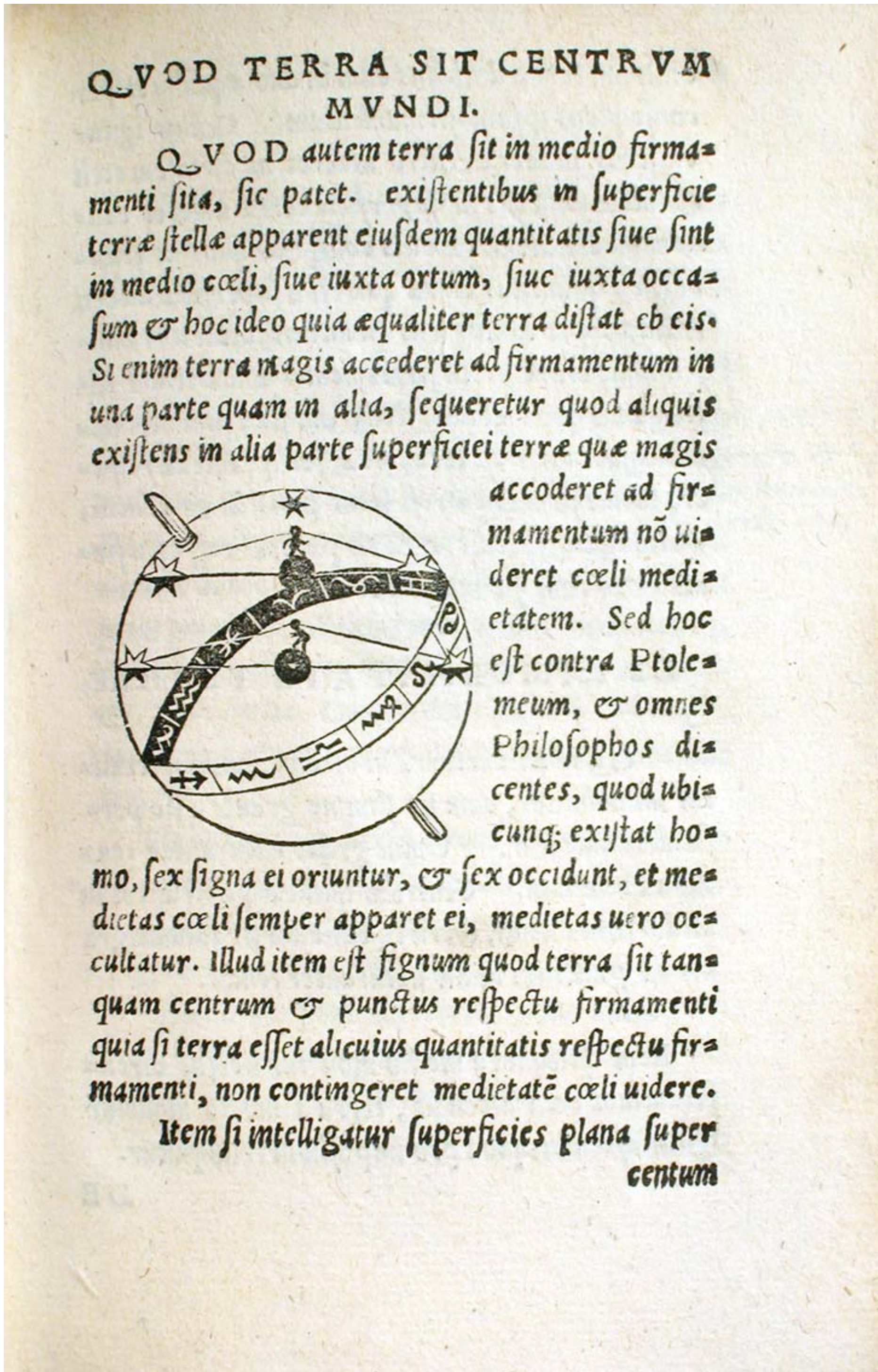


Commoditas, quia omnium corporum Iſoperimetrorum ſphæra maximum eſt, omnium etiam formarum rotunda capaciſsima eſt, quoniam igitur maximum & rotundum, ideo capaciſsimum, unde cum mundus omnia contineat, talis forma fuit illi utilis & commoda.

Neceſsitas, quoniam ſi Mundus eſſet alterius formæ quam rotundæ, ſcilicet trilateræ, uel quadrilateræ, uel multilateræ, ſequerentur duo impoſsibilia, ſcilicet, quod aliquis locus eſſet uacuus, & corpus ſine loco, quorum utrunq; eſt falſum, ſicut patet in angulis eleuatis & circumuolutis.

Item

Figure 6: Argument for the sphericity of the cosmos. If it were any other shape, the angles would alternately protrude and leave void spaces as it rotated. From Sacrobosco, *Iohannis de Sacro Busto Libellus de Sphera* (Wittenberg: Iohannes Crato, 1550), fol. B5v.



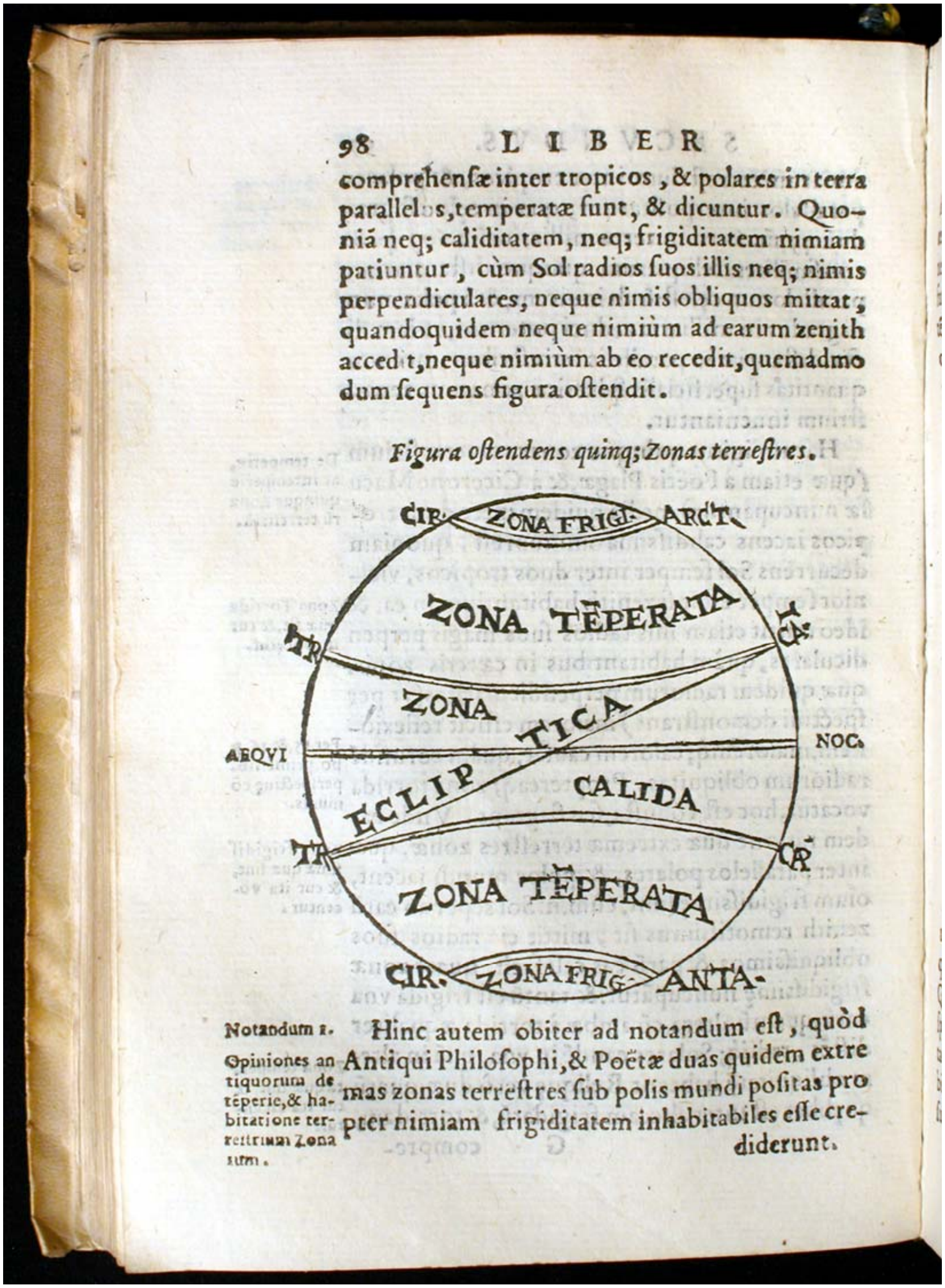
QVOD TERRA SIT CENTRVM MVNDI.

QVOD autem terra ſit in medio firmamenti ſita, ſic patet. exiſtentibus in ſuperficie terræ ſtellæ apparent eiuſdem quantitatis ſiue ſint in medio cœli, ſiue iuxta ortum, ſiue iuxta occaſum & hoc ideo quia æqualiter terra diſtat ab eis. Si enim terra magis accederet ad firmamentum in una parte quam in alia, ſequeretur quod aliquis exiſtens in alia parte ſuperficiei terræ quæ magis accoderet ad firmamentum nō uideret cœli medietatem. Sed hoc eſt contra Ptolemeum, & omnes Philoſophos dicentes, quod ubicunq; exiſtat homo, ſex ſigna ei oriuntur, & ſex occidunt, et medietas cœli ſemper apparet ei, medietas uero occultatur. Illud item eſt ſignum quod terra ſit tanquam centrum & punctus reſpectu firmamenti quia ſi terra eſſet alicuius quantitatis reſpectu firmamenti, non contingeret medietatē cœli uidere.

Item ſi intelligatur ſuperficies plana ſuper centum

Figure 7: Argument for the Earth's centrality. To the central observer, all stars appear to be equally distant and six signs of the zodiac (covering half of a great circle) will always be visible. To the observer removed from the center, the star at the meridian appears closer and the number of zodiacal signs visible will not equal six. From Sacrobosco, *Liber Iohannis de Sacro Busto, de Sphera* (Wittenberg: Iosephus Clug, 1534), fol. B7r.

Figure 8: Arguments for the sphericity of the Earth and of the element water. Top left: observers see different celestial objects because they have different horizons. Top right: during a lunar eclipse, seen simultaneously by both observers, it is still daylight at A, but evening at B. Bottom: as the ship sails away from land, a sailor on the deck sees objects on land dip below the horizon while a sailor atop the mast can still see the building. From Sacrobosco, *Iohannis de Sacro Busto Libellus de Sphera* (Wittenberg: Iohannes Crato, 1550), fol. B3r.



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comprehenſæ inter tropicos, & polares in terra parallel s, temperatæ ſunt, & dicuntur. Quoniã neq; caliditatem, neq; frigiditatem nimiam patiuntur, cùm Sol radios ſuos illis neq; nimis perpendiculares, neque nimis obliquos mittat; quandoquidem neque nimiùm ad earum zenith acced t, neque nimiùm ab eo recedit, quemadmodum ſequens figura oſtendit.

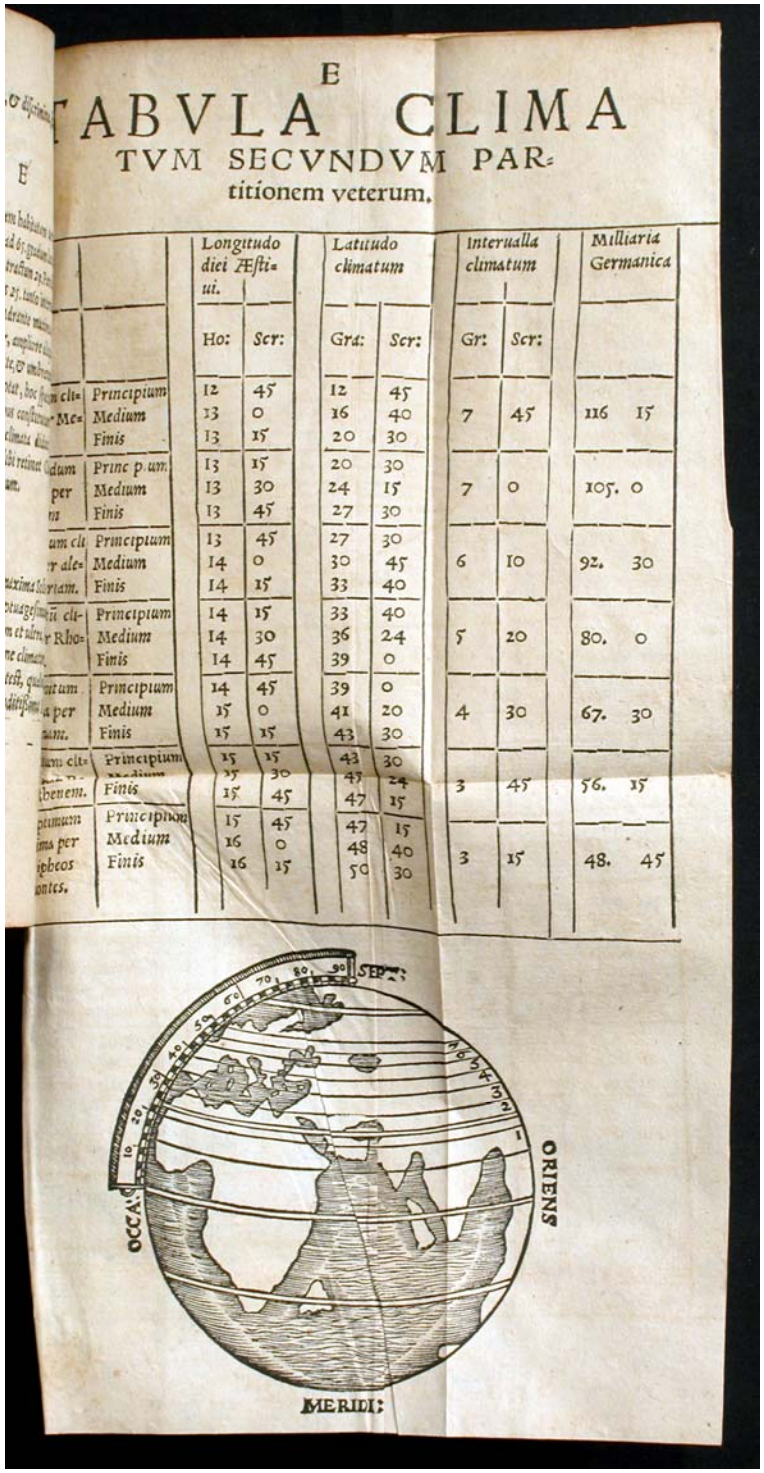
Figura oſtendens quinq; Zonas terreſtres.

Notandum 1.

Opiniones antiquorum de tẽperie, & habitatione terreſtrium Zonarum.

Hinc autem obiter ad notandum eſt, quòd Antiqui Philoſophi, & Poëtæ duas quidem extremas zonas terreſtres ſub polis mundi poſitas propter nimiam frigiditatem inhabitabiles eſſe crediderunt.

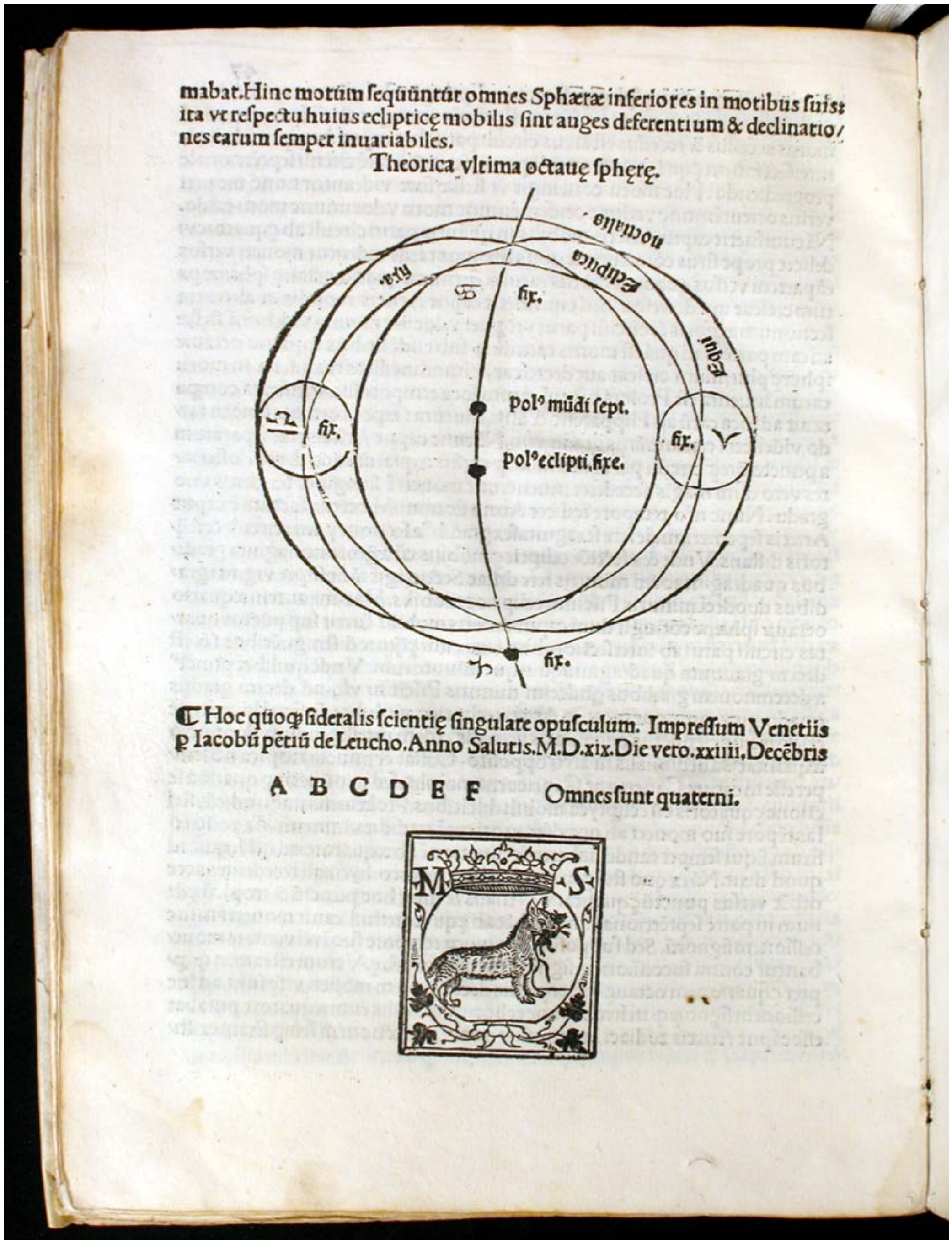
Figure 9: The five zones of the Earth. The frigid zones are at the extreme north and south. The two torrid regions on either side of the equator are merged to form a single zone. Most life is in the temperate zones, though scholars speculate that a marginal existence may be possible elsewhere. The zones are defined by the tropics and the Arctic and Antarctic circles. From Francesco Barozzi, *Cosmographica in quatuor libros* (Venice: G. Perchacini, 1585), fol. G1v.


E

TABVLA CLIMATVM SECVNDVM PARtitionem veterum.

	Longitudo diei Æstiui. Ho:	Scr:	Latitudo climatum Gra:	Scr:	Interualla climatum Gr:	Scr:	Milliaria Germanica
Principium	12	45	12	45			
Medium	13	0	16	40	7	45	116 15
Finis	13	15	20	30			
Princ p.um	13	15	20	30			
Medium	13	30	24	15	7	0	105. 0
Finis	13	45	27	30			
Principium	13	45	27	30			
Medium	14	0	30	45	6	10	92. 30
Finis	14	15	33	40			
Principium	14	15	33	40			
Medium	14	30	36	24	5	20	80. 0
Finis	14	45	39	0			
Principium	14	45	39	0			
Medium	15	0	41	20	4	30	67. 30
Finis	15	15	43	30			
Principium	15	15	43	30			
[illegible]	15	30	45	24	3	45	56. 15
Finis	15	45	47	15			
Principium	15	45	47	15			
Medium	16	0	48	40	3	15	48. 45
Finis	16	15	50	30			

Figure 10: The seven climes defined by the duration of the longest day. Climes are of unequal width; the two right-hand columns give each clime's width in degrees and German miles. Parts of the globe in the uninhabitable frigid and torrid zones lie beyond the climes. From Peucer, *Elementa doctrina* (Wittenberg: Iohannes Crato, 1569), plate opposite 266.


mabat.Hinc motũm sequũntur omnes Sphæræ inferiores in motibus suis: ita vt respectu huius eclipticę mobilis sint auges deferentium & declinatio/nes earum semper inuariabiles.

Theorica vltima octauę sphęrę.

℃ Hoc quoq; sideralis scientię singulare opusculum. Impressum Venetiis ꝑ Iacobũ pẽtiũ de Leucho. Anno Salutis.M.D.xix.Die vero.xxiiii.Decẽbris

A B C D E F Omnes sunt quaterni.

Figure 11: Medieval trepidation as described by Peurbach. The small circles are inscribed around the "fixed" mean equinoxes where the equinoctial crosses the ecliptic of the ninth sphere. The two large circles touching the edges of the small circles represent successive positions of the ecliptic of the eighth sphere (i.e., the visible ecliptic). As the small circles rotate, the visible equinoxes trepidate along the equator and the solstices alternately approach and withdraw from the north celestial pole (*polus mundi sept.*). From Sacrobosco, *Sphaera mundi compendium foeliciter inchoat* (Venice: I. Petreius, 1519), fol. 47v.

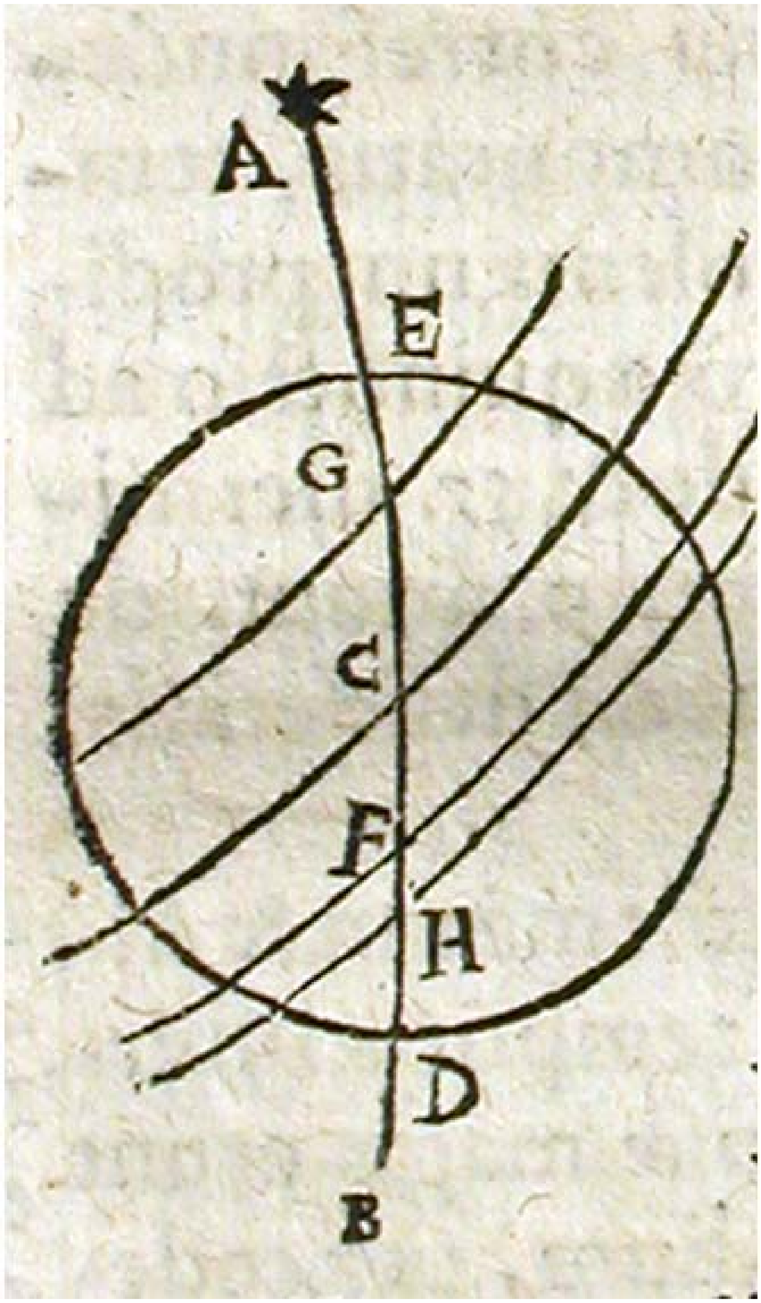


Figure 12: Observed effects of Copernicus's theory of trepidation. AB is the ecliptic, crossed by the equinoctial. The mean equinox, C, precesses uniformly away from the star A, at the same time that the true equinox trepidates within the circle drawn around C. The observed effects of the Alfonsine-Peurbach trepidation theory are similar, except that the equinoctial is fixed and the ecliptic is mobile. From Maestlin's annotated edition of the *Narratio prima*, printed with Kepler, *Mysterium cosmographicum* (Tübingen: Georgius Bruppenbachius, 1596), 106.

Figure 13: The usefulness of mathematics. The mathematician labors over a globe, the product of geography; on the wall over his head hang a quadrant (left) and astrolabe (right). The border is ornamented with additional instruments and objects of mathematical study: a triangle, music, constellations and planets. In the background ships are steered with the aid of celestial objects. Note the high sides and multiple masts typical of ocean-crossing ships of the fifteenth and sixteenth centuries. From Sacrobosco, *Spera volgare novamente tradotta* (Venice: Bartholomeo Zanetti, 1537), frontispiece.

NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum spacio circũ currens. In medio uero omnium residet Sol. Quis enim in hoc

pulcherrimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximã Luna cũ terra cognationẽ habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

Figure 14: The heliocentric system of *De revolutionibus*. Like the Ptolemaic cosmological section in figure 1, this schematic diagram omits the multiple circles needed for precise calculation. From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 9v.

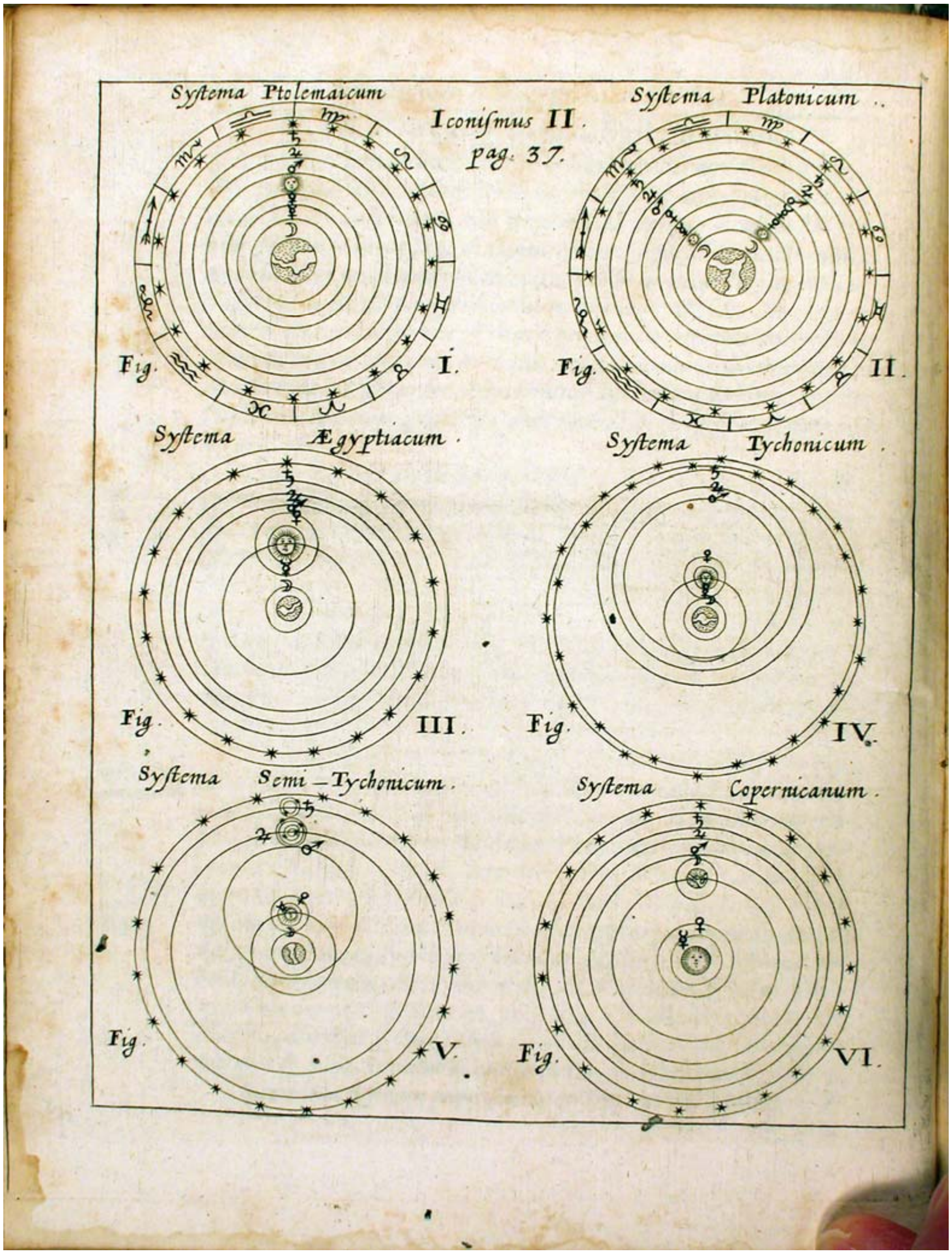
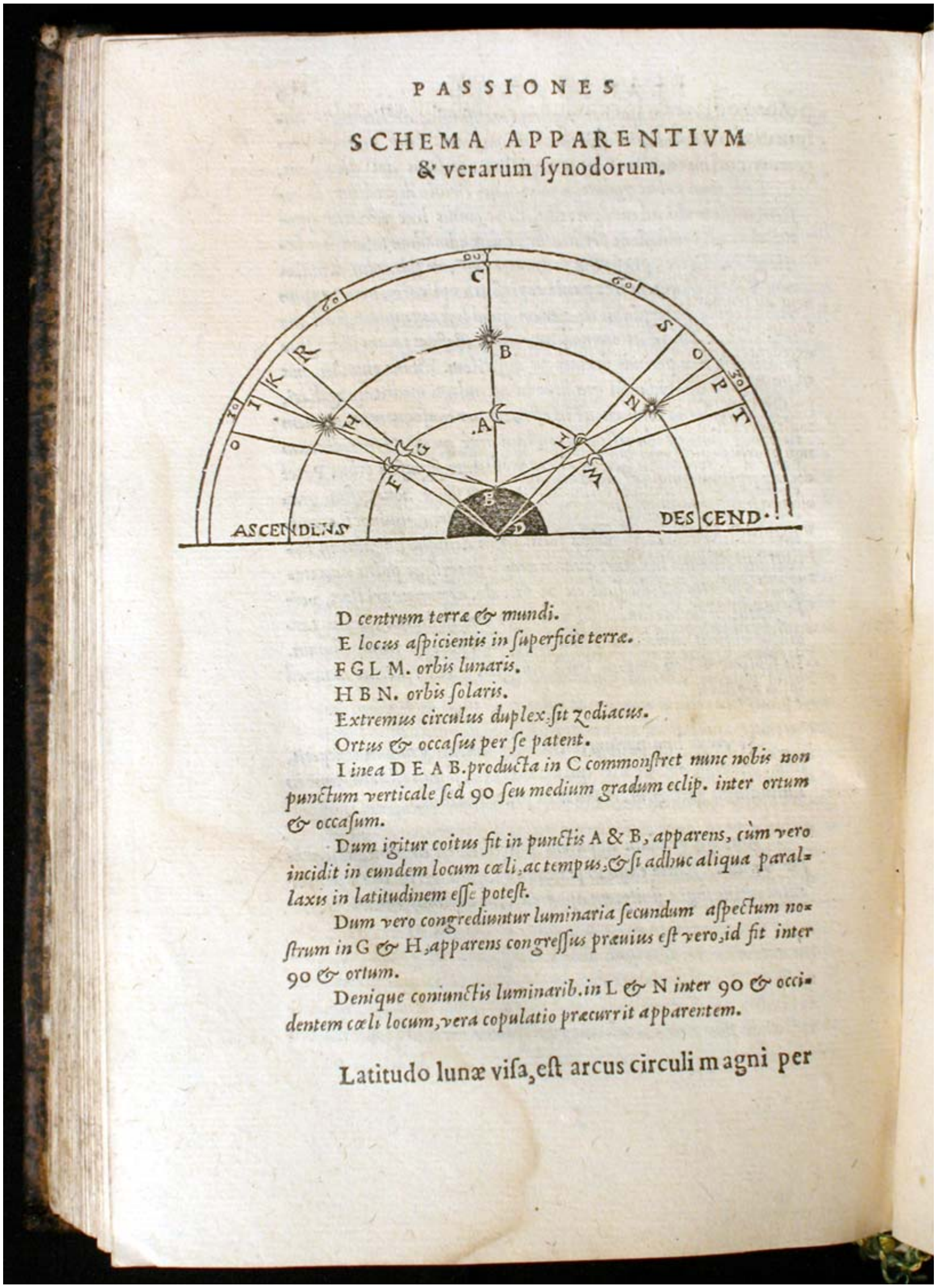


Figure 15: Cosmologies of early modern Europe. Top row (left) Ptolemaic: geocentric with Sun fourth from center; (right) Platonic: geocentric with Sun second from center. Center row (left) "Egyptian" system of Martianus Capella and others: geocentric with Mercury and Venus heliocentric; (right) Tychonic: fully geoheliocentric, with Sun and Mars overlapping. Bottom row (left) Semi-Tychonic: geocentric with Mercury, Venus, and Mars geocentric; circles around outer planets denote satellites discovered after invention of telescope ca. 1609; (right) Copernican: fully heliocentric. From Athanasius Kircher, *Iter extaticum coeleste* (Herbipoli: Sumptibus J. Andr. & Wolffg. Endterorum Haeredibus, 1660), plate 12.


PASSIONES

SCHEMA APPARENTIVM
& verarum ſynodorum.

D centrum terræ & mundi.
E locus aſpicientis in ſuperficie terræ.
F G L M. orbis lunaris.
H B N. orbis ſolaris.
Extremus circulus duplex ſit zodiacus.
Ortus & occaſus per ſe patent.
Linea D E A B. producta in C commonſtret nunc nobis non punctum verticale ſed 90 ſeu medium gradum eclip. inter ortum & occaſum.
Dum igitur coitus fit in punctis A & B, apparens, cùm vero incidit in eundem locum cœli, ac tempus, & ſi adhuc aliqua parallaxis in latitudinem eſſe poteſt.
Dum vero congrediuntur luminaria ſecundum aſpectum noſtrum in G & H, apparens congreſſus prævius eſt vero, id fit inter 90 & ortum.
Denique coniunctis luminarib. in L & N inter 90 & occidentem cœli locum, vera copulatio præcurrit apparentem.

Latitudo lunæ viſa, eſt arcus circuli magni per

Figure 16: Lunar parallax. The Moon is the only celestial object close enough to have parallax readily observed with the naked eye. Lines of sight show that the observer's location on the Earth's surface determines where the Moon appears against the backdrop of the fixed stars, and whether a solar eclipse will be seen. From Peurbach, *Theoricae novae planetarum Purbacchii Germani ab Erasmo Reinholdo Salveldensi pluribus figuris aucta* (Paris: Carolus Perier, 1553), fol. 130v.

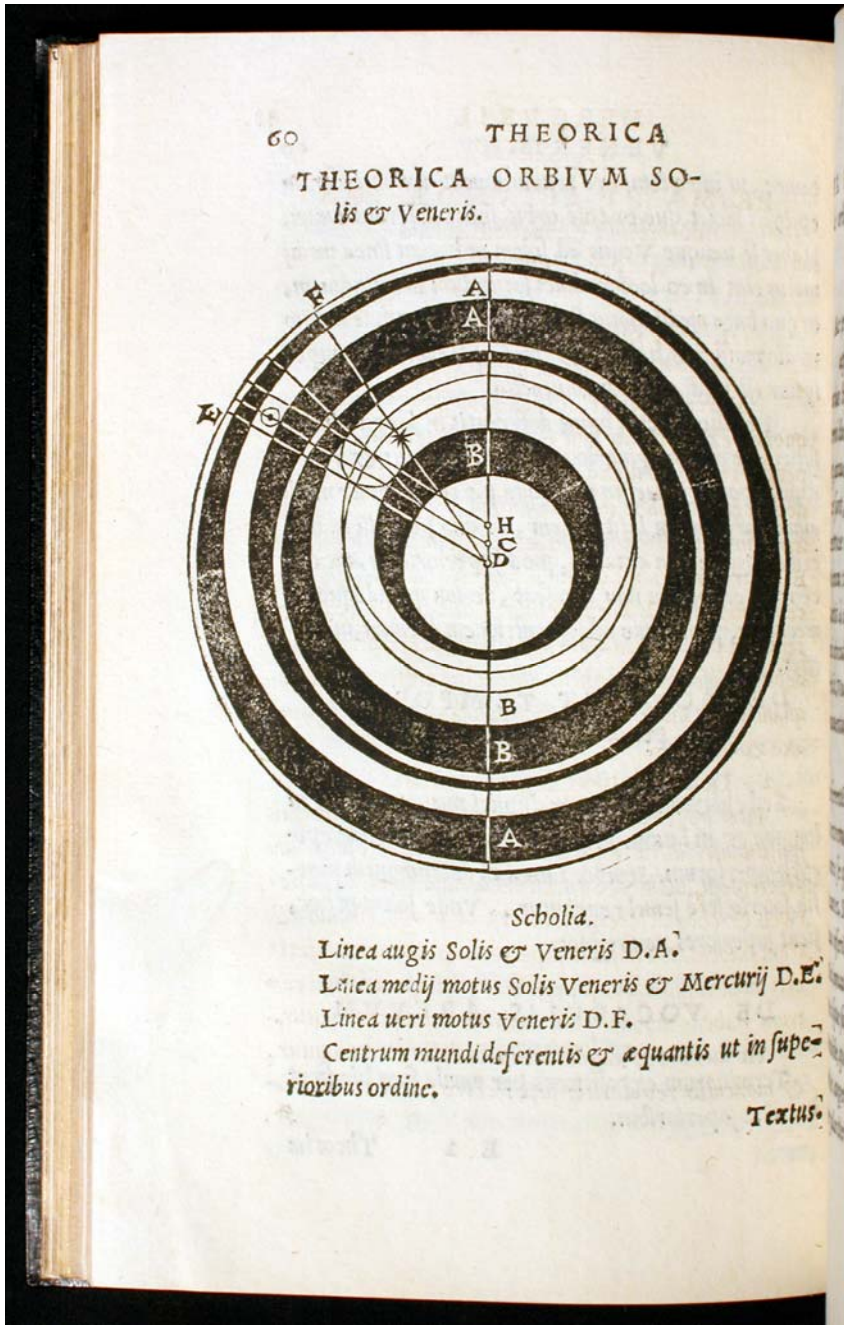
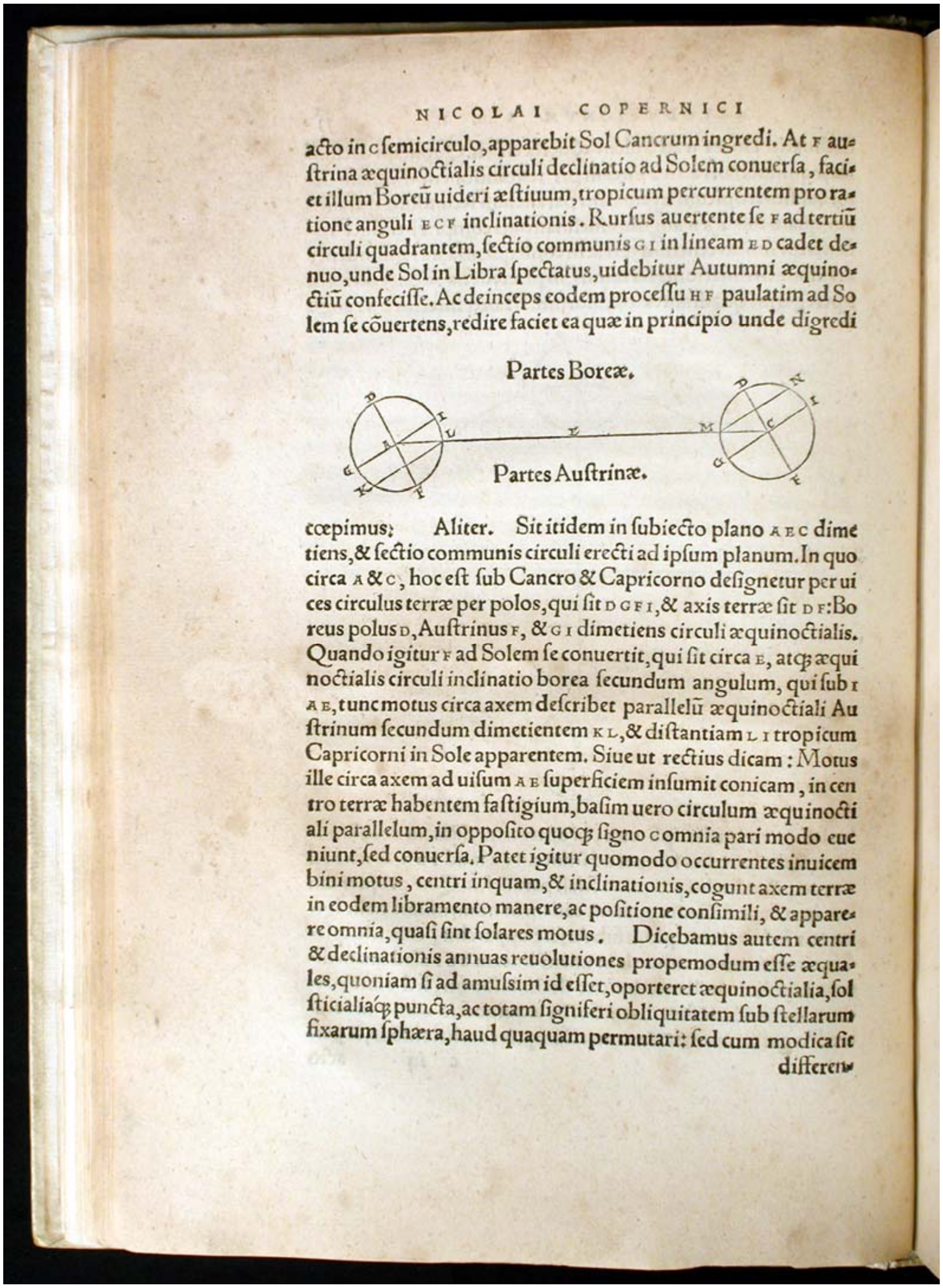


Figure 17: Combined Ptolemaic models for Sun and Venus. The two outer black orbs enclose the eccentric solar deferent; the two inner black orbs enclose the eccentric deferent of Venus with its epicycle shown as a circle. The diagram illustrates the concept of bounded elongation. Both planets have the same line of mean motion, DE, which indicates their approximate direction as seen from D, the Earth. Because its epicycle always appears close to the Sun, Venus remains in the vicinity of the Sun. This image incorporates the "nesting principle," showing how complicated planetary models can be made concentric without intervening space. From Peurbach, *Theoricae novae planetarum* (Paris: Christianus Wechelus, 1543), 60.



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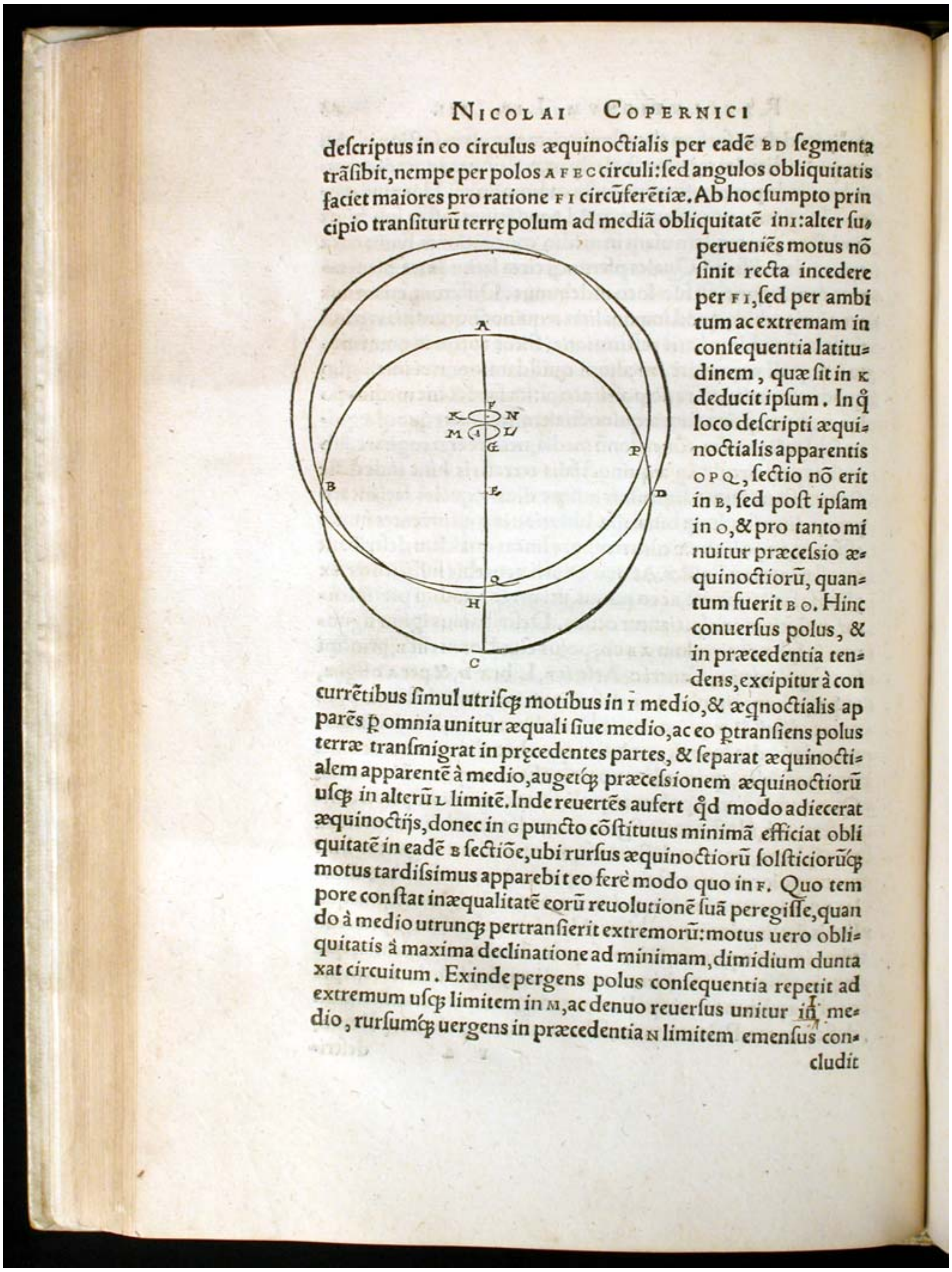
acto in c ſemicirculo, apparebit Sol Cancrum ingredi. At F auſtrina æquinoctialis circuli declinatio ad Solem conuerſa, faciet illum Boreũ uideri æſtiuum, tropicum percurrentem pro ratione anguli ECF inclinationis. Rurſus auertente ſe F ad tertiũ circuli quadrantem, ſectio communis GI in lineam ED cadet denuo, unde Sol in Libra ſpectatus, uidebitur Autumni æquinoctiũ confeciſſe. Ac deinceps eodem proceſſu HF paulatim ad Solem ſe cõuertens, redire faciet ea quæ in principio unde digredi

cœpimus; Aliter. Sit itidem in ſubiecto plano AEC dimetiens, & ſectio communis circuli erecti ad ipſum planum. In quo circa A & C, hoc eſt ſub Cancro & Capricorno deſignetur per uices circulus terræ per polos, qui ſit DGFI, & axis terræ ſit DF: Boreus polus D, Auſtrinus F, & GI dimetiens circuli æquinoctialis. Quando igitur F ad Solem ſe conuertit, qui ſit circa E, atq; æquinoctialis circuli inclinatio borea ſecundum angulum, qui ſub IAE, tunc motus circa axem deſcribet parallelũ æquinoctiali Auſtrinum ſecundum dimetientem KL, & diſtantiam LI tropicum Capricorni in Sole apparentem. Siue ut rectius dicam: Motus ille circa axem ad uiſum AE ſuperficiem inſumit conicam, in centro terræ habentem faſtigium, baſim uero circulum æquinoctiali parallelum, in oppoſito quoq; ſigno C omnia pari modo eueniunt, ſed conuerſa. Patet igitur quomodo occurrentes inuicem bini motus, centri inquam, & inclinationis, cogunt axem terræ in eodem libramento manere, ac poſitione conſimili, & apparere omnia, quaſi ſint ſolares motus. Dicebamus autem centri & declinationis annuas reuolutiones propemodum eſſe æquales, quoniam ſi ad amuſsim id eſſet, oporteret æquinoctialia, ſolſticialiaq; puncta, ac totam ſigniferi obliquitatem ſub ſtellarum fixarum ſphæra, haud quaquam permutari: ſed cum modica ſit

differen-

Figure 18: Copernicus’s annual motion of inclination. As the Earth moves around the Sun, E, its axis DF maintains approximately the same alignment toward the north celestial pole). Copernicus assigns it an annual rotation on an axis (not shown) perpendicular to the plane of the ecliptic AEC. A slight difference between the period of this motion and the length of the sidereal year causes DF to shift its alignment gradually, which we see as precession of the equinoxes. From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 11v.



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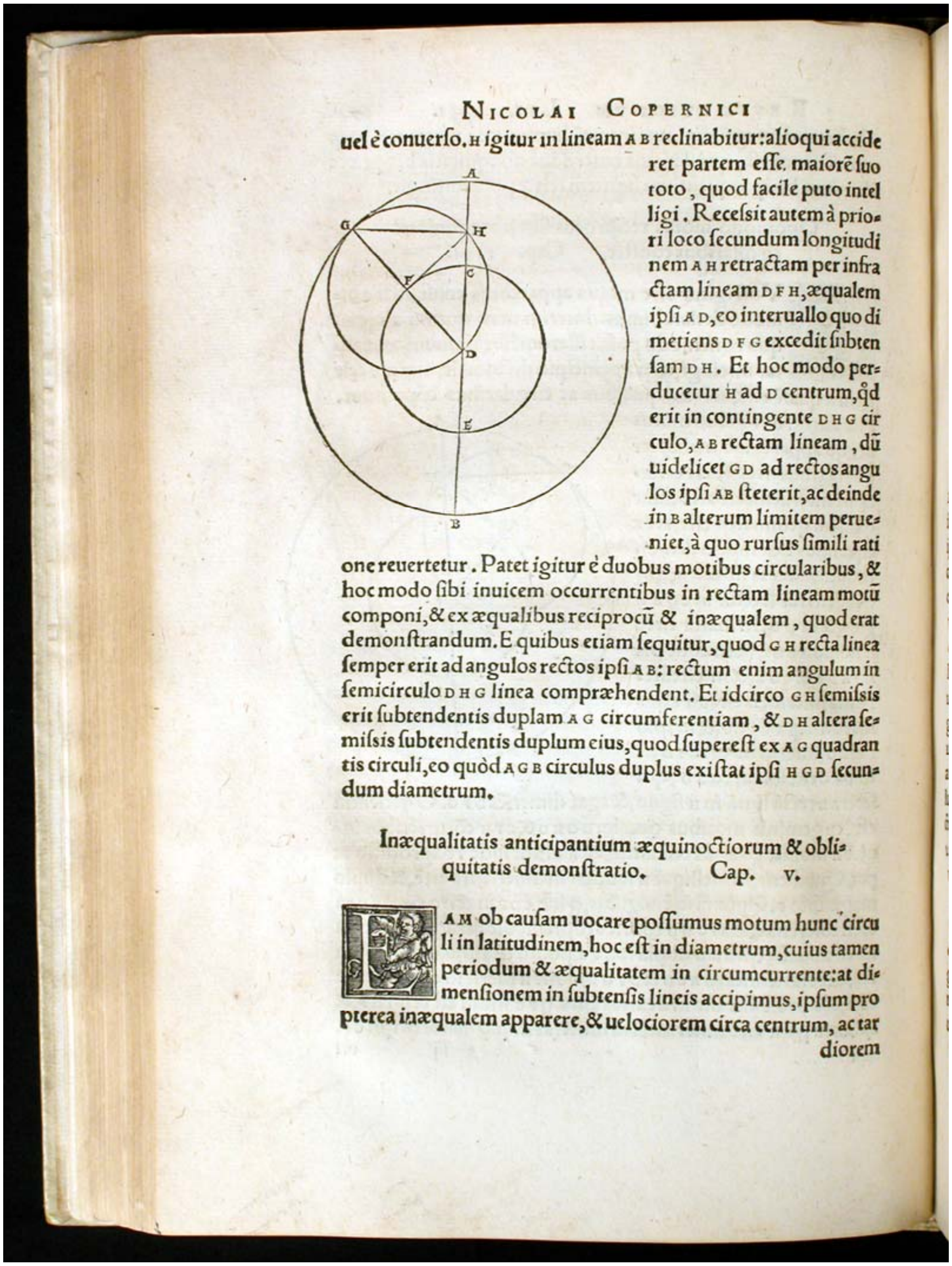
deſcriptus in eo circulus æquinoctialis per eadẽ B D ſegmenta trãſibit, nempe per polos A F E C circuli: ſed angulos obliquitatis faciet maiores pro ratione F I circũferẽtiæ. Ab hoc ſumpto principio tranſiturũ terrę polum ad mediã obliquitatẽ in I: alter ſuperueniẽs motus nõ ſinit recta incedere per F I, ſed per ambitum ac extremam in conſequentia latitudinem, quæ ſit in K deducit ipſum. In q̊ loco deſcripti æquinoctialis apparentis O P Q, ſectio nõ erit in B, ſed poſt ipſam in O, & pro tanto minuitur præceſsio æquinoctiorũ, quantum fuerit B O. Hinc conuerſus polus, & in præcedentia tendens, excipitur à concurrẽtibus ſimul utriſq; motibus in I medio, & æqnoctialis apparẽs ꝑ omnia unitur æquali ſiue medio, ac eo ꝑtranſiens polus terræ tranſmigrat in pręcedentes partes, & ſeparat æquinoctialem apparentẽ à medio, augetq; præceſsionem æquinoctiorũ uſq; in alterũ L limitẽ. Inde reuertẽs aufert q̊d modo adiecerat æquinoctijs, donec in G puncto cõſtitutus minimã efficiat obliquitatẽ in eadẽ B ſectiõe, ubi rurſus æquinoctiorũ ſolſticiorũq; motus tardiſsimus apparebit eo ferè modo quo in F. Quo tempore conſtat inæqualitatẽ eorũ reuolutionẽ ſuã peregiſſe, quando à medio utrunq; pertranſierit extremorũ: motus uero obliquitatis à maxima declinatione ad minimam, dimidium duntaxat circuitum. Exinde pergens polus conſequentia repetit ad extremum uſq; limitem in M, ac denuo reuerſus unitur in I medio, rurſumq; uergens in præcedentia N limitem emenſus concludit

Figure 19: Librations of the pole. Each motion taken separately would cause the pole to oscillate; combined, they create a figure eight. The Earth's pole begins at the top at F. It swings down and left to K, then reverses its horizontal swing to move through the center to L, where it reverses its horizontal swing again to move to the bottom. At this point it has completed the 1,717-year cycle and is halfway through the 3,434-year cycle. It reverses direction and begins swinging towards the top, moving through M and N to finish at F. From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 66v.



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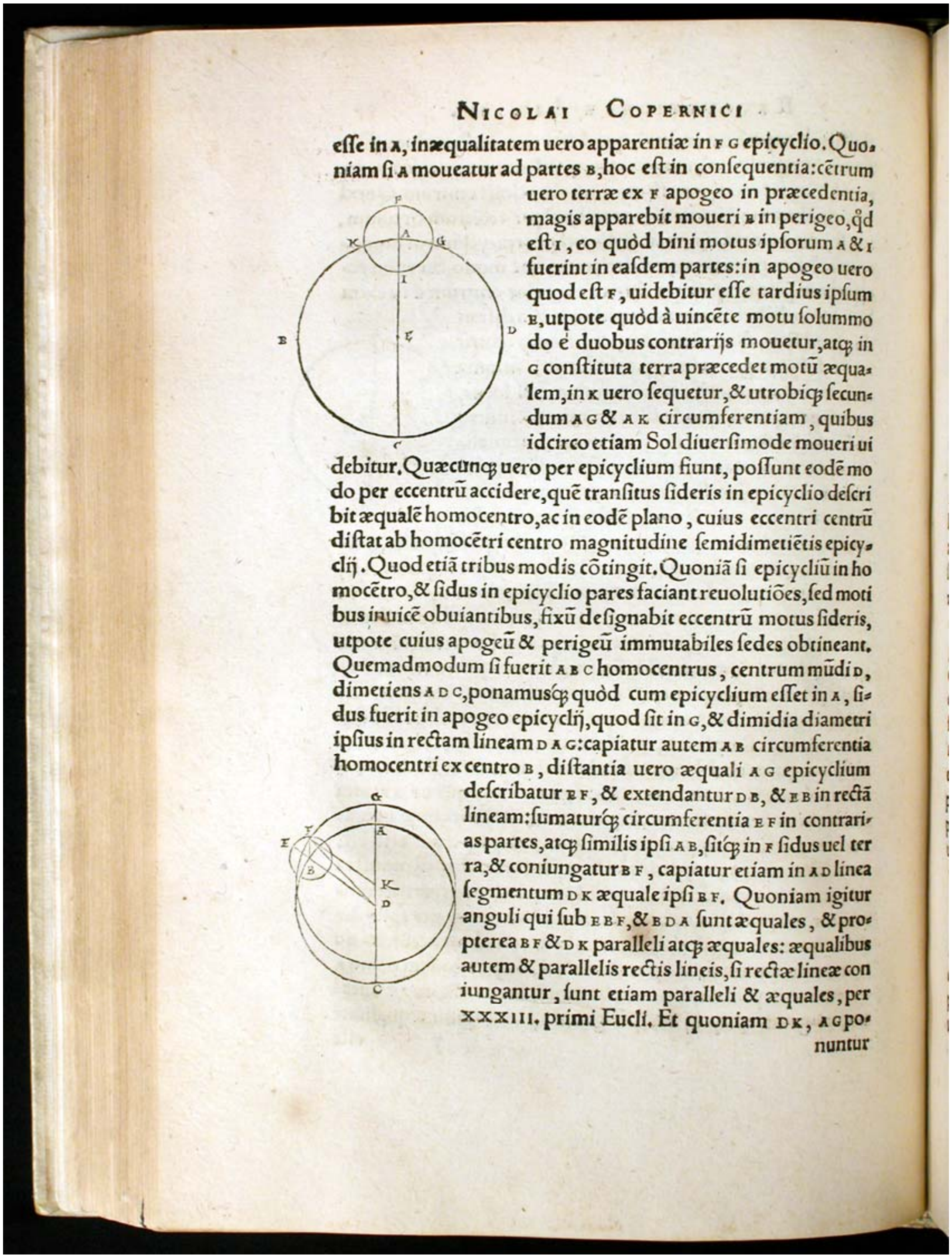
uel è conuerſo. H igitur in lineam A B reclinabitur: alioqui accideret partem eſſe maiorē ſuo toto, quod facile puto intelligi. Receſsit autem à priori loco ſecundum longitudinem A H retractam per infractam lineam D F H, æqualem ipſi A D, eo interuallo quo dimetiens D F G excedit ſubtenſam D H. Et hoc modo perducetur H ad D centrum, q̃d erit in contingente D H G circulo, A B rectam lineam, dū uidelicet G D ad rectos angulos ipſi A B ſteterit, ac deinde in B alterum limitem perueniet, à quo rurſus ſimili ratione reuertetur. Patet igitur è duobus motibus circularibus, & hoc modo ſibi inuicem occurrentibus in rectam lineam motū componi, & ex æqualibus reciprocū & inæqualem, quod erat demonſtrandum. E quibus etiam ſequitur, quod G H recta linea ſemper erit ad angulos rectos ipſi A B: rectum enim angulum in ſemicirculo D H G linea compræhendent. Et idcirco G H ſemiſsis erit ſubtendentis duplam A G circumferentiam, & D H altera ſemiſsis ſubtendentis duplum eius, quod ſupereſt ex A G quadrantis circuli, eo quòd A G B circulus duplus exiſtat ipſi H G D ſecundum diametrum.

Inæqualitatis anticipantium æquinoctiorum & obliquitatis demonſtratio. Cap. v.

IAM ob cauſam uocare poſſumus motum hunc circuli in latitudinem, hoc eſt in diametrum, cuius tamen periodum & æqualitatem in circumcurrente: at dimenſionem in ſubtenſis lineis accipimus, ipſum propterea inæqualem apparere, & uelociorem circa centrum, ac tardiorem

Figure 20: Ṭūsī couple. In one version, the large circle with diameter AB is twice the size of the small circle with diameter DG. As circle AB rotates counterclockwise, circle DG rotates clockwise in half the time. Point H on the circumference of the small circle oscillates along line AB. Straight-line motion can be generated in the heavens from a combination of circular motions. Copernicus used this device to explain the librations of the poles. From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 67v.



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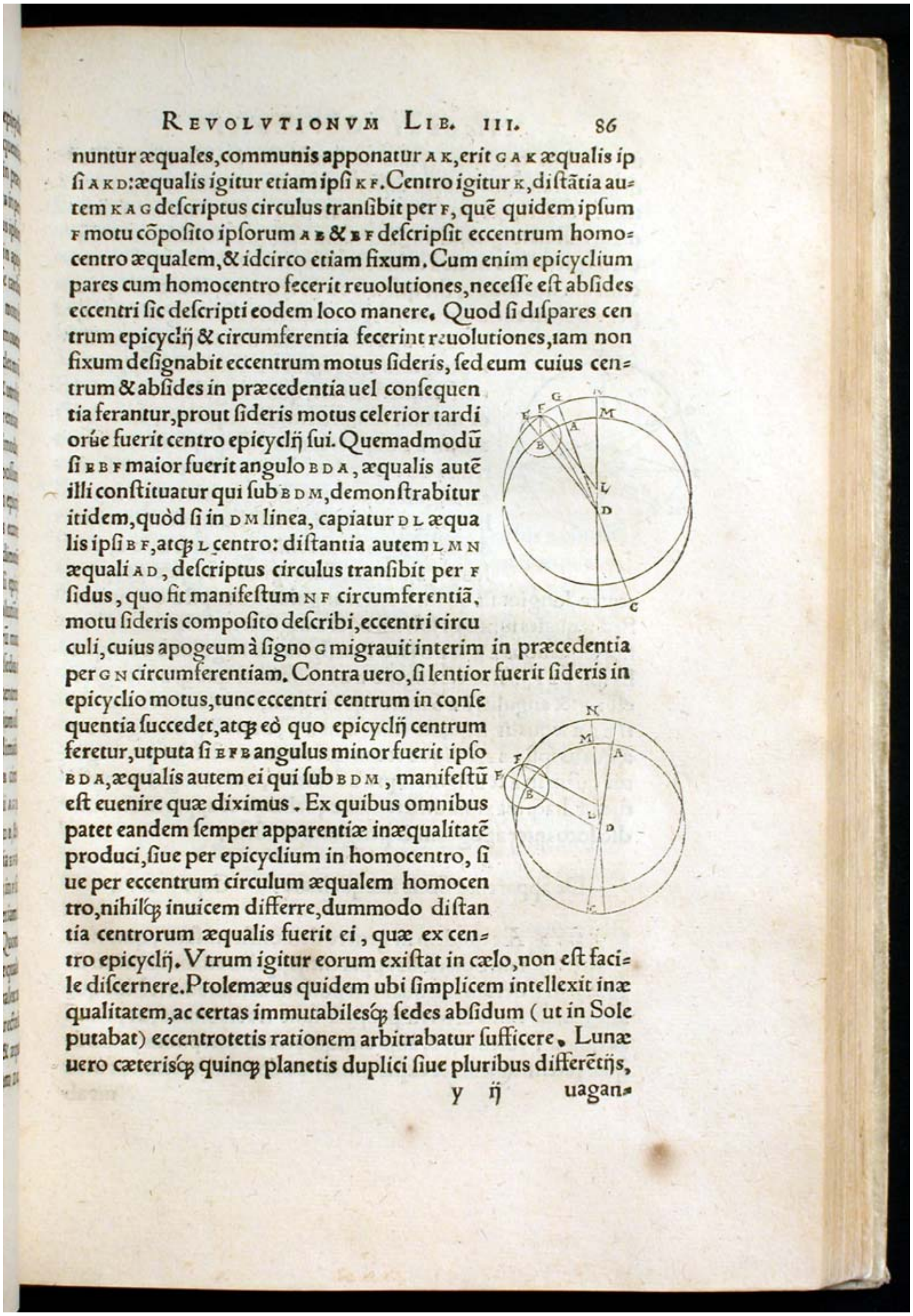
esse in A, inæqualitatem uero apparentiæ in F G epicyclio. Quoniam si A moueatur ad partes B, hoc est in consequentia: cētrum uero terræ ex F apogeo in præcedentia, magis apparebit moueri B in perigeo, q̄d est I, eo quòd bini motus ipsorum A & I fuerint in easdem partes: in apogeo uero quod est F, uidebitur esse tardius ipsum B, utpote quòd à uincēte motu solummodo è duobus contrarijs mouetur, atq; in G constituta terra præcedet motū æqualem, in K uero sequetur, & utrobiq; secundum A G & A K circumferentiam, quibus idcirco etiam Sol diuersimode moueri uidebitur. Quæcunq; uero per epicyclium fiunt, possunt eodē modo per eccentrū accidere, quē transitus sideris in epicyclio describit æqualē homocentro, ac in eodē plano, cuius eccentri centrū distat ab homocētri centro magnitudine semidimetiētis epicyclij. Quod etiā tribus modis cōtingit. Quoniā si epicycliū in homocētro, & sidus in epicyclio pares faciant reuolutiōes, sed motibus inuicē obuiantibus, fixū designabit eccentrū motus sideris, utpote cuius apogeū & perigeū immutabiles sedes obtineant. Quemadmodum si fuerit A B C homocentrus, centrum mūdi D, dimetiens A D C, ponamusq; quòd cum epicyclium esset in A, sidus fuerit in apogeo epicyclij, quod sit in G, & dimidia diametri ipsius in rectam lineam D A G: capiatur autem A B circumferentia homocentri ex centro B, distantia uero æquali A G epicyclium describatur E F, & extendantur D B, & E B in rectā lineam: sumaturq; circumferentia E F in contrarias partes, atq; similis ipsi A B, sitq; in F sidus uel terra, & coniungatur B F, capiatur etiam in A D linea segmentum D K æquale ipsi B F. Quoniam igitur anguli qui sub E B F, & B D A sunt æquales, & propterea B F & D K paralleli atq; æquales: æqualibus autem & parallelis rectis lineis, si rectæ lineæ coniungantur, sunt etiam paralleli & æquales, per XXXIII. primi Eucli. Et quoniam D K, A G ponuntur

Figure 21: Apollonius's theorem. Bottom: epicycle on concentric deferent with both periods equal. D is the center of the universe; B is the center of the epicycle. The epicycle is carried counterclockwise on the deferent, while the epicycle rotates clockwise. The planet, at F, will trace out the eccentric circle with center K. This version of an epicyclic model is equivalent to a simple eccentric. From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 85v.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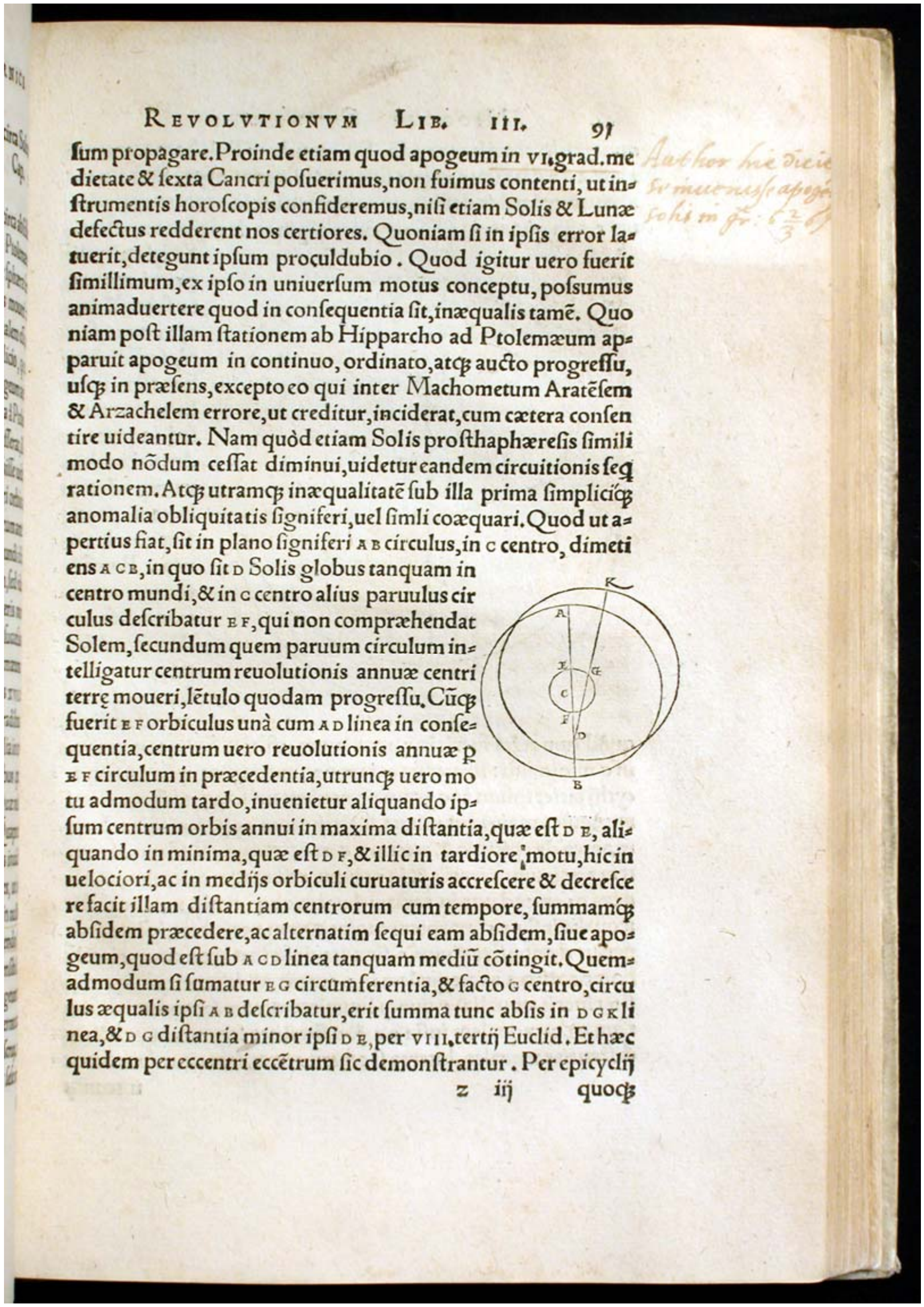
nuntur æquales, communis apponatur A K, erit G A K æqualis ip
si A K D: æqualis igitur etiam ipsi K F. Centro igitur K, distãtia au-
tem K A G descriptus circulus transibit per F, quẽ quidem ipsum
F motu cõposito ipsorum A B & B F descripsit eccentrum homo-
centro æqualem, & idcirco etiam fixum. Cum enim epicyclium
pares cum homocentro fecerit reuolutiones, necesse est absides
eccentri sic descripti eodem loco manere. Quod si dispares cen
trum epicyclij & circumferentia fecerint reuolutiones, iam non
fixum designabit eccentrum motus sideris, sed eum cuius cen-
trum & absides in præcedentia uel consequen
tia ferantur, prout sideris motus celerior tardi
orúe fuerit centro epicyclij sui. Quemadmodũ
si E B F maior fuerit angulo B D A, æqualis autẽ
illi constituatur qui sub B D M, demonstrabitur
itidem, quòd si in D M linea, capiatur D L æqua
lis ipsi B F, atq; L centro: distantia autem L M N
æquali A D, descriptus circulus transibit per F
sidus, quo fit manifestum N F circumferentiã,
motu sideris composito describi, eccentri circu
culi, cuius apogeum à signo G migrauit interim in præcedentia
per G N circumferentiam. Contra uero, si lentior fuerit sideris in
epicyclio motus, tunc eccentri centrum in conse
quentia succedet, atq; eò quo epicyclij centrum
feretur, utputa si E F B angulus minor fuerit ipso
B D A, æqualis autem ei qui sub B D M, manifestũ
est euenire quæ diximus. Ex quibus omnibus
patet eandem semper apparentiæ inæqualitatẽ
produci, siue per epicyclium in homocentro, si
ue per eccentrum circulum æqualem homocen
tro, nihilq; inuicem differre, dummodo distan
tia centrorum æqualis fuerit ei, quæ ex cen-
tro epicyclij. Vtrum igitur eorum existat in cælo, non est faci-
le discernere. Ptolemæus quidem ubi simplicem intellexit inæ
qualitatem, ac certas immutabilesq; sedes absidum (ut in Sole
putabat) eccentrotetis rationem arbitrabatur sufficere. Lunæ
uero cæterisq; quinq; planetis duplici siue pluribus differẽtijs,
y ij uagan-

Figure 22: Advanced version of Apollonius's theorem. Top: epicycle on concentric with shorter deferent period, equivalent to eccentric with apogee N moving clockwise. Bottom: epicycle on concentric with longer deferent period, equivalent to eccentric with apogee moving counterclockwise. From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 86r.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ſum propagare. Proinde etiam quod apogeum in VI. grad. me dietate & ſexta Cancri poſuerimus, non fuimus contenti, ut inſtrumentis horoſcopis conſideremus, niſi etiam Solis & Lunæ defectus redderent nos certiores. Quoniam ſi in ipſis error latuerit, detegunt ipſum proculdubio. Quod igitur uero fuerit ſimillimum, ex ipſo in uniuerſum motus conceptu, poſſumus animaduertere quod in conſequentia ſit, inæqualis tamē. Quoniam poſt illam ſtationem ab Hipparcho ad Ptolemæum apparuit apogeum in continuo, ordinato, atq; aucto progreſſu, uſq; in præſens, excepto eo qui inter Machometum Aratēſem & Arzachelem errore, ut creditur, inciderat, cum cætera conſentire uideantur. Nam quòd etiam Solis proſthaphæreſis ſimili modo nōdum ceſſat diminui, uidetur eandem circuitionis ſeq rationem. Atq; utramq; inæqualitatē ſub illa prima ſimpliciq; anomalia obliquitatis ſigniferi, uel ſimili coæquari. Quod ut apertius fiat, ſit in plano ſigniferi AB circulus, in C centro, dimetiens ACB, in quo ſit D Solis globus tanquam in centro mundi, & in C centro alius paruulus circulus deſcribatur EF, qui non compræhendat Solem, ſecundum quem paruum circulum intelligatur centrum reuolutionis annuæ centri terræ moueri, lētulo quodam progreſſu. Cūq; fuerit EF orbiculus unà cum AD linea in conſequentia, centrum uero reuolutionis annuæ p EF circulum in præcedentia, utrunq; uero motu admodum tardo, inuenietur aliquando ipſum centrum orbis annui in maxima diſtantia, quæ eſt DE, aliquando in minima, quæ eſt DF, & illic in tardiore motu, hic in ueloc iori, ac in medijs orbiculi curuaturis accreſcere & decreſcere facit illam diſtantiam centrorum cum tempore, ſummamq; abſidem præcedere, ac alternatim ſequi eam abſidem, ſiue apogeum, quod eſt ſub ACD linea tanquam mediū cōtingit. Quemadmodum ſi ſumatur EG circumferentia, & facto G centro, circulus æqualis ipſi AB deſcribatur, erit ſumma tunc abſis in DGK linea, & DG diſtantia minor ipſi DE, per VIII. tertij Euclid. Et hæc quidem per eccentri eccētrum ſic demonſtrantur. Per epicyclij

z iij quoq;

Figure 23: Copernican solar model. D is the Sun. The Earth’s deferent moves on the “small circle” with center C and diameter EF (second anomaly). Currently it is at G; the line DGK is the apsidal line and K is the aphelion. At the same time, C moves uniformly around the Sun (first anomaly). From Copernicus, *De revolutionibus orbium coelestium* (Nuremberg: Ioh. Petreius, 1543), fol. 91r.

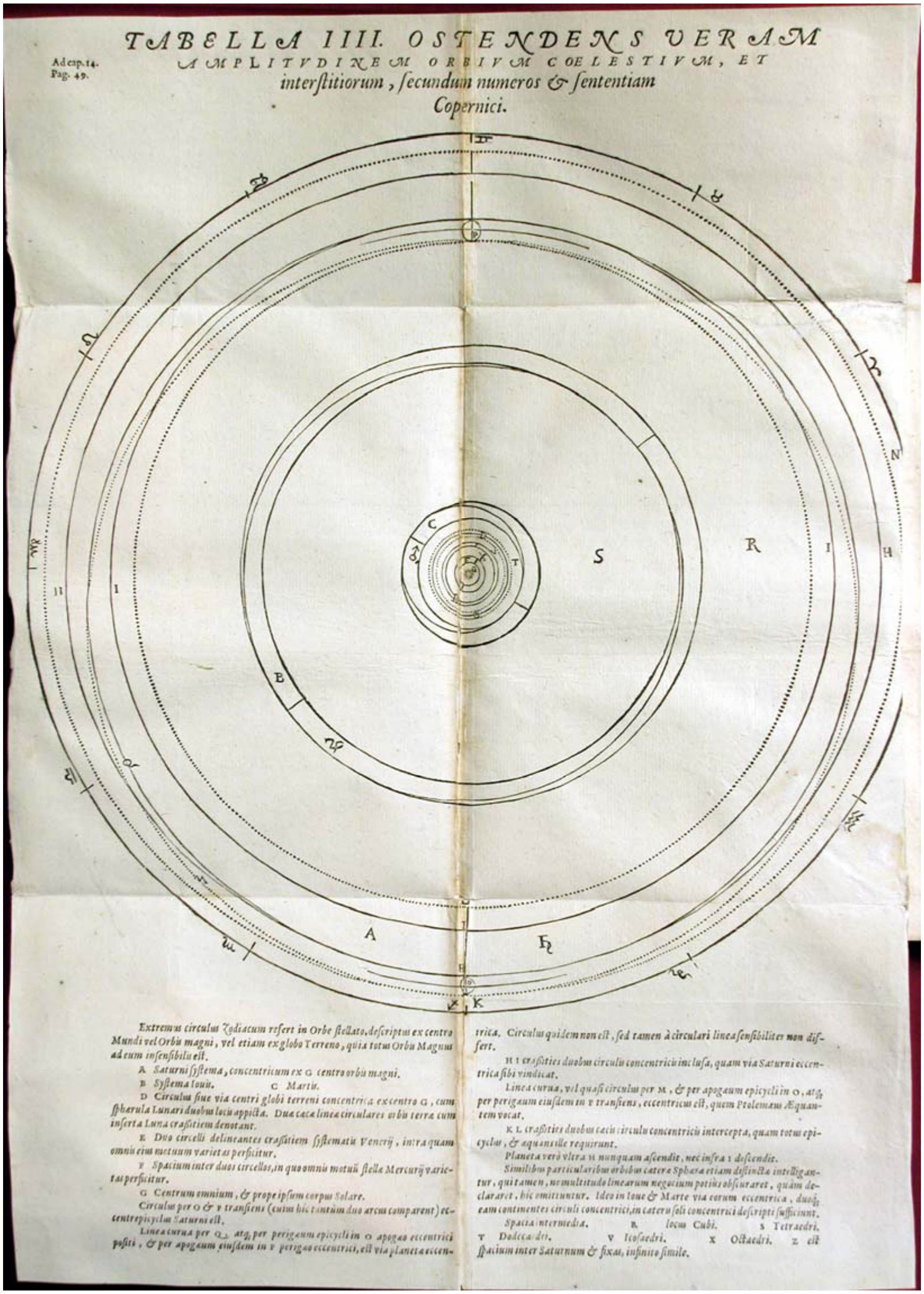

Figure 24: Kepler's version of Copernican cosmology. Unlike most cosmological diagrams of the time, this one represents planetary orbs to scale. Note that the least and greatest distances for planetary orbs leave large intervening gaps. From Kepler, *Dissertationum prodromus cosmographicarum, continens Mysterium cosmographicum* (Tübingen: Georgius Gruppenbachius, 1596), plate 4.

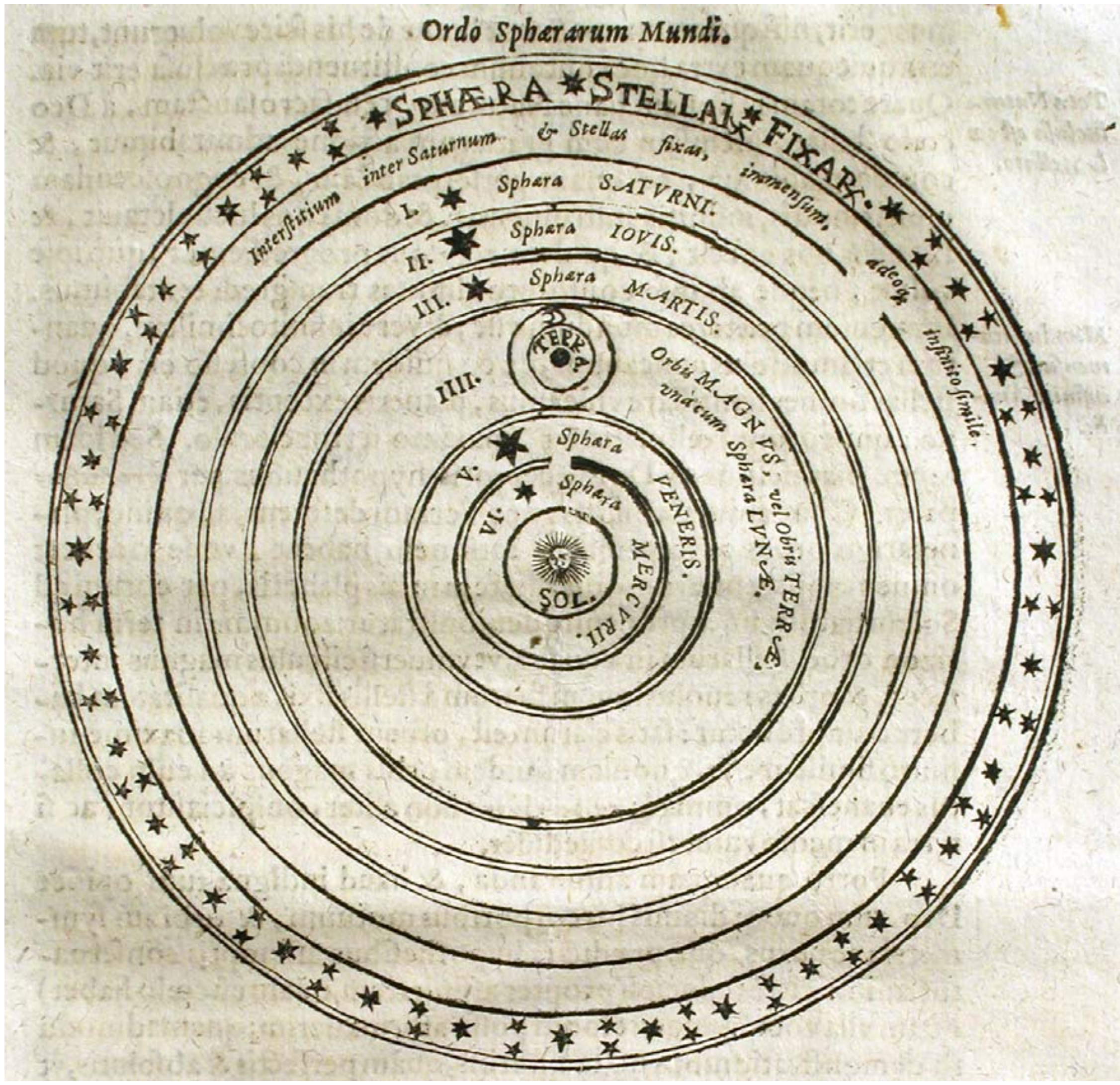

Figure 25: Maestlin's version of Copernican cosmology. Double lines are spaces between planetary orbs. Below the starry orb is the "Space between Saturn and the fixed stars, immense, and similar to something infinite." Not all stars are the same distance from the center. Because the sphere of stars does not rotate, it can be of indefinite thickness. Unlike Kepler's diagram, this illustration is not to scale. From Kepler, *Dissertationum prodromus cosmographicarum, continens Mysterium cosmographicum* (Tübingen: Georgius Gruppenbachius, 1596), 117.

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APPENDIX ONE

PHILIP MELANCHTHON'S PREFACE TO SACROBOSCO'S *COMPUTUS* (1538)
Corpus Reformatorum 3: 573-76, No. 1715.

Johannes de Sacrobosco's little book on the reckoning of the year or as it is commonly called: Computus Ecclesiasticus. With a preface by Philip Melanchthon.[1]

To the most learned man D. Achilles Gasser of Lindau, Teacher of Medicine, from his friend Philip Melanchthon.

It is a vast and evident advantage to understand the established reckoning of the year. What might have been the confusion of present businesses, contracts, treaties, legal affairs, what darkness, if there were no distinction of years and months? In histories, how much fog would there have been, with the counting of years abolished? The beginning of the world could not be known, the introduction of religion not discerned, the changes of empires not distinguished. It is clear, however, that knowledge of these things is necessary to religion and to many parts of life. For which reason I cannot marvel enough at the ingratitude, or the perversity rather, of the many, who censure this doctrine on the celestial motions and the description of the year.

Further, both the greatness of the advantage and the judgments of the wisest Princes and most learned men, who set the year in order with great diligence, ought to

[1] A partial translation of the nontechnical sections of this preface can be found in Kraai, "Rheticus' Heliocentric Providence," 88-89.

influence the ignorant, so that with the ear and also with the soul they might shrink back from those most foolish and jeering insults which are spoken against the good arts and divinely demonstrated things. We see indeed that there were great cares on the part of greatly praised Princes that they describe the year as rightly as possible, so that times could be distinguished and the memories of things propagated and preserved. On that account also Solon set the year of Athens in order according to the judgment of Thales when the appointments of the equinoxes had been established. This reckoning was corrected after two hundred years by Eudoxus, who was Plato's contemporary. But Caesar boasts of his law, in the work of Lucanus, that the calendar of Eudoxus was surpassed in his time.[2] For indeed, although there had been diverse reckonings--Egyptian, Greek, and Arabic--Caesar, when Sosigenes had been called in consultation, devised a new one by far more satisfactory than the others. For the months of the Egyptian year had thirty days each, and there were added on every year five Epacts. There was neither a fixed reckoning of intercalation, nor a fixed beginning of the year.[3]

The months of the Greek year agree with the moon, without a fixed number of days. Moreover, there were added on eleven Epacts, from which they collected the *embolimon* [embolismic month].[4]

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[2] "I always find time for the zones and high reaches of stars and sky, nor by Eudoxus' calendar shall *my* year be outdone!" M. Annaeius Lucanus, *Pharsalia*, transl. Jane Wilson Joyce (Ithaca: Cornell University Press, 1993), 275-76.

[3] The Egyptian year consists of twelve months of thirty days, plus five epagomenal days not in any month. Melanchthon calls the latter *epacts*, which in this context refers to the five days by which the months fall short of the year. In addition, because the Egyptian year contains exactly 365 days and the solar year contains about 365 1/4 days, the Egyptian year falls out of step with the solar year at a rate of about one day in four years. In the absence of further intercalation, the first day of the Egyptian year gradually moves backwards through the seasons over a period of about 1460 years, the famous "Sothic cycle." E. J. Bickerman, *Chronology of the Ancient World*, 2nd ed. (Ithaca: Cornell University Press, 1980), 40-43.

[4] The lunar month is about 29 1/2 days; twelve lunar months create a year of 354 days, eleven days short of the tropical year. The "epacts" or intercalary days were "collected" to create an intercalary thirteenth

The Arabic reckoning was more learned than these two. For the Arabic months vary by turns, in such a way that the former has twenty-nine days, the following indeed thirty. Afterwards there were added eleven Epacts, from which they collected the *embolimon*.[5]

Now Caesar saw in all these descriptions not only that it was an inconvenient uncertainty for labors--for the beginnings of the same months were different according to different people--but also that the equinoxes were excessively slippery and speeding. On this account he established that form of the year--which we use almost to this day, even if from so great an interval the work now involves emendation--so that the beginning of the year and month would be fixed, and the day of the equinox might be connected in this fashion [i.e., the calculated day would correspond to the true time of the equinox], so that it would just barely vary over several generations. Do we reject this attentiveness in the greatest men, or believe it has been taken up in vain curiosity without a weighty reason? Nor truly could these reckonings, either the Egyptian, or the Greek, or the Arabic, or the Roman, be computed without great knowledge of celestial motions. For my part, I have no doubt that it is done by the plan of God alone, so that the first parents might record the

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month. Since intercalations in Greek cities were made according to decree, not by a fixed cycle, Greek calendars tended to be chaotic. Many details of Greek calendars, which differed from polis to polis, remain obscure. Bickerman, *Chronology*, 27-38.

[5] Melanchthon describes a system of alternating "hollow" twenty-nine day months and "full" thirty-day months. He probably meant by the "Arabic" calendar something like the situation described by Jacob Christmann, a commentator on al-Farghānī, in which an originally pure lunar calendar was modified by Babylonian and Hebrew practices: "The Arabs have pure, unmixed lunar years, that is, collected from twelve lunar periods; consequently, if the amount of one period is known, the whole quantity of the Arabic year also becomes known. But the Arabs spread abroad, and in some way for their calendar they take advantage of the Turkish, from the ancient Hebrew and Babylonian. . . ." "Arabes puros putos habent annos lunares, hoc est, ex duodecim periodis lunaribus confectos: proinde si quantitas vnius sciatur, tota quoque anni Arabici quantitatis innotescit. Didicerunt autem Arabes, & qui eorum calendario vtuntur Turcae, à veteribus Hebreis & Babyloniis. . . ." From al-Farghānī, *Muhamedis alfragani arabis chronological et astronomica elementa … additus est commentarius, qui rationem calendarii … explicat* (Frankfurt: Andreae Wecheliheredes, Claudium Marnium, & Ioann. Aubrium, 1590), 194 (my translation).

years so diligently at the start of the world, namely, so that future generations could think back to the beginning of the world, and count those small periods of time. Likewise [it is done] so that the differences of religion could be contemplated, so that the course of the promises of celestial things and of histories could be understood. If anyone believes that these reasons are insufficiently weighty, verily he has a Cyclopic mind.[6] Let us admit therefore that the first parents, who excelled in wisdom and piety, were divinely urged to observing and propagating the distinction of years. Nor, however, could the year be enclosed by the turning points of the equinoxes and be rightly described without knowledge of celestial motions. Wherefore it is necessary for them [i.e., the first parents] to have been devoted to study of the entire doctrine of celestial motions. Now what kind of arrogance is it to despise the discoveries, not only of other great men, but also of the first parents, who were guides for the human race and pointers-out of true religion and of true wisdom?

Therefore studious youths should love this doctrine of celestial motions, and should judge it to be useful for life, both on account of the description of the year and because of other reasons besides. For whereas some disapprove of *ton mantiken* [divination], we observe the unlearned condemning by the same account even the doctrine of motions. Certainly contempt of this whole Philosophy is confirmed in unrefined people. But even if I shall not debate concerning prophetic matters in this place, nevertheless if we wish to appraise rightly, this very doctrine of motions truly is

[6] The ignorant and brutish Cyclops who denies God's providence, was a favorite image for Melanchthon. In a biography of Galen, for instance, he asks "What shall I say here of those Cyclopes who not only despise the inquiry [i.e., of medicine], but also the use and the remedies? They inflict savagery upon their bodies by enormous gluttony, immoderate vigils and in other ways and then, like the Stoics, they say that health and life are ruled by fate and that diseases are not acquired by our vices, nor repelled by diligence and remedies, but by fate." *Orations*, transl. Salazar, 213.

especially *mantike* [divination]. It gives evidence that an eternal mind is artisan and governor of the world, and that we are formed for knowledge of God and for immortality. Or is this *mantike* to be rejected? What more truly is fitting to prophets than to confirm true and pious opinions about God in men's spirits? For which reason let us acknowledge that this same divinatory doctrine of motions is useful for life and for morals. Let it be a soundly prophetic thing, as for example the *kraseis* [mixing] of bodies is both to judge innate qualities from some notable conjunction of stars, or to predict storms, on account of which "Sometimes a day is a stepmother, sometimes a mother."[7] However, it is more prophetic to strengthen minds by means of the revealed, most certain laws of motions, so that truly they may establish that there is a God who sets in order, who governs these motions, who wishes to be known by men for the sake of whose utility he put together these varieties of motions; so much the more, when he invites us to knowledge of himself, he promises rewards for the good and punishments for the impious. But I have argued these things abundantly elsewhere.[8] I return to the former oration about the description of the year.

I greatly approve of Georg Ioachim Rheticus' plan, which attached, to the little book on the Sphere, the reckoning of the year written by the same author Iohannes de Sacro Busto. For, as I said before, it is useful to have an established reckoning of the year for many reasons. So great was the care still taken formerly in the Church of its affair, that Cyril asserted as true that it was established in the Synod that every year the

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[7] I have taken the translation of the Greek quote from Kraai, "Rheticus' Heliocentric Providence," 89, where the source is identified as Hesiod, *Works and Days* 825.

[8] For instance, in the prefaces to Sacrobosco's *Sphaera* and Puerbach's *Theoricae novae*.

Alexandrian Bishop should indicate to the Roman [Bishop] the set day of the equinox.[9] On which account, whereas in the Alexandrian school at that time studies of this Philosophy still flourished, at Rome they were indeed not known in like manner.

Further, this little book, since it presents the reckoning of the year, also assists the studious in the doctrine of the motions of the Sun and Moon. To you, moreover, Georg wished especially to dedicate this little book, so that he might show that he was mindful of your old friendship, and so that in this place he might thank you with my voice, because you encouraged him in these studies, when you were moved by celestial signs, when indeed he entered upon a greatly different way of life and was shrinking back from this Philosophy. For which reason he decides he owes you a great deal, because he was called back to these arts by your authority. You will welcome, therefore, this gift from a friend and companion of most honorable studies, with it being a great pleasure, because it includes something of those arts which produce great honor for you among the learned. I know, moreover, that the little book has been corrected by a man endowed with exceptional learning and virtue, Caspar Bornerus, whose diligence is wonderful, both in all duties of life, and likewise in studies of the good arts. Wherefore the readers, for whom this little book is about to be poured out, owe thanks to him. Farewell. In the month of August, the year 1538.

[9] Melanchthon has in mind Cyril, Bishop of Alexandria (ca. 375-444). Cyril's authentic letter to the Council of Carthage in 419 was doctored in the early Middle Ages during a dispute over methods of reckoning Easter. According to the spurious additions, the Council of Nicaea approved a nineteen-year Alexandrian Cycle for the Church calendar. Together with the pseudo-Cyrillic Easter Tables, the *Epistola Cyrilli* lent authority to the Alexandrian method in the west (Wallis, in Bede, *Reckoning of Time*, xlviii-xlix, lix-lx). Bede quoted the letter and accepted that because of superior Egyptian skills, the bishop of Alexandria was given responsibility for the correct calculation of the date of Easter, in *Reckoning of Time*, 118, 121-22.

APPENDIX TWO

COSMIC SIZES AND DISTANCES ACCORDING TO PTOLEMY

Ptolemy calculates sizes and distances for all celestial bodies in Book 1, Part 2 of the *Planetary Hypotheses* and for the Sun and Moon in Book 5 of the *Almagest*. Values marked with an asterisk (*) come from the *Almagest* and are accompanied by chapter references in brackets. Distances are given in Earth radii (e.r.). Except where noted, only maximum distances are given, since the minimum distance is equal to the next maximum. Diameters and volumes are given in units where the Earth equals one.

	Distance	**Diameter**	**Volume**
Fixed Stars (1st Magnitude)	ca. 20,000 (minimum)	4 1/2 + 1/20 (least possible)	96 1/6 + 1/8 (least possible)
Saturn	19, 865	4 1/4 + 1/20	79 + 1/2
Jupiter	14,187	4 1/3 + 1/40	82 1/2 + 1/4 + 1/20
Mars	8,820	1 + 1/7	1 + 1/2
Sun	1,260 (max) 1,210 (mean)* [15] 1,160 (min)	5 + 1/2* [16]	ca. 170* [16] 166 + 1/3
Venus	1,079	1/4 + 1/20	1/44
Mercury	166 (max) 64 (min)	1/27	1/19,683
Moon (*Almagest*)	64;10 (max)* [15] 33;33 (min)* [17]	1 in (3 + 2/5)* [16]	1 in (39 1/4)* [16]
Moon (*Hypotheses*)	64 (max) 33 (min)	1/4 + 1/24	1/40
Axis of Shadow	268	-----	-----
Elementary Sphere	33	-----	-----

APPENDIX THREE

COSMIC DISTANCES ACCORDING TO *DE REVOLUTIONIBUS*

Copernicus calculates absolute distances for the Sun and Moon in *De revolutionibus* Book 4, chapters 15 through 21. For the remaining planets he gives distances in terms of the size of the Earth's circle. His procedures can be found in Book 5, chapters 9 (Saturn), 14 (Jupiter), 19 (Mars), 21 (Venus), and 27 (Mercury). I have calculated absolute values using the mean terrestrial distance of 1,142 Earth radii, rounding off to the nearest whole number. Distances are given in Earth radii (e.r.) and reflect the planet's greatest and least distances from the center of the great orb of the Earth, with the exception of the Moon, where distances are from the Earth. My values differ slightly from those calculated by Van Helden, probably because of different standards of rounding off at each step of calculation.[1]

	Minimum	Mean	Maximum
Saturn	9,878	10, 478	11,077
Jupiter	5,687	5,960	6,233
Mars	1,569	1,736	1,902
Earth (Sun)	1,105	1,142	1,179
Venus	798	822	845
Mercury	300	430[2]	516
Moon	55;8	-----	65;30
Axis of Shadow	-----	265	-----

[1] Van Helden, *Measuring the Universe*, 46.

[2] Because of complications in the Mercury model, Copernicus calculates a separate mean apogee distance instead of averaging the least and greatest distances to find a proportional mean.

APPENDIX FOUR

TRANSLATIONS FROM GEORG JOACHIM RHETICUS'S
NARRATIO PRIMA (EXCERPTS)

This translation follows the text of the critical edition published by Hugonnard-Roche and Verdet in the *Studia Copernicana*.[1] Where this leads to a deviation from the text of the first edition of the *Narratio*, it is almost always because they have amended the text following the errata sheet or incorporated the emendations made by Michael Maestlin in the 1596 edition. For the translation itself, I have consulted with the translations of Rosen (English) and Hugonnard-Roche and Verdet (French), though it should be noted that the French translation is also based in part on the English.

The monarchies of the world are changed according to the motion of the center of the eccentric.

Let me add also some prophecy. We see that all monarchies began when the center of the eccentric was in some notable place of this small circle. Thus, when the Sun's eccentricity was greatest, the Roman government changed to a Monarchy, and just as that one decreased, so also this one became weak, as if growing old, and even passed away. When it reached the mean quadrant and boundary, the Mohammedan rule was founded, and thus another great empire commenced and grew very swiftly according to

[1] Rheticus, *Narratio prima*, ed. with transl. and commentary by Henri Hugonnard-Roche and Jean-Pierre Verdet with Michel-Pierre Lerner and Alain Segonds, *Studia Copernicana* 20 (Wrocław: Polish Academy of Sciences, 1982).

the rule of motion. Soon in a hundred years, when the eccentricity will be least, this empire too will finish its period, so that around this time it is at the greatest height, from which, God willing, it will tumble down equally swiftly with a heavier fall. Moreover, when the center of the eccentric reaches the other mean boundary, we hope for the coming of our Lord Jesus Christ. For near the moment of the creation of the world it was here, and this calculation does not differ much from the saying of Elijah, who prophesied by divine instigation that the world will endure only 6,000 years, in which time about two revolutions are completed. And so it appears that this small circle most truly is that wheel of Fortune by whose turning the monarchies of the world may take their beginnings and be changed as well. For in this manner the greatest changes in the whole history of the world are perceived as if written on this circle. Shortly I shall hear from you personally, God willing, how it may be discovered from great conjunctions and other learned divinations of what kind those next empires are bound to be, whether established with fair or tyrannical laws.

Principal reasons why the hypotheses of Ancient Astronomers should be withdrawn.

Now first, the undoubted precession of the equinoxes (as you have heard) and the change of the obliquity of the ecliptic led him [i.e., Copernicus] to believe that he should assume that the appearances in heaven largely could follow from, or at least be saved most appropriately by the motion of the earth.

In the second place, because that same diminution of the eccentricity of the Sun is observed with a similar rule and proportionately in the eccentricities of the remaining planets.

Next, because it appears that the planets have the centers of their own deferents near the Sun, as though at the middle of the universe. Moreover, it is quite sufficiently evident that the most Ancient ones also realized the same things (granted that I pass over the Pythagoreans in silence for the time being) from this example: because Pliny, undoubtedly having followed the best Authorities, said that Venus and Mercury do not depart from the Sun further than fixed and appointed limits for this reason: because they have their apsides directed around the Sun, and for which reason it is proper that the mean motion of the Sun happens to them too.[2]

Since he [Pliny] says truly that the path of Mars is not observable, and besides the remaining difficulties in the emendation of the motion of Mars, it is not doubtful but that it sometimes admits a diversity of aspects [parallax] sometimes greater than the Sun itself. It seems impossible for the earth to possess the center of the world. Again, even if this same thing may also be inferred easily from Saturn and Jupiter by their disposition in relation to us at rising in morning and evening, for all that it is observed chiefly and most greatly in the differences of risings of Mars. Because the star of Mars has a quite dim light, it does not deceive the eyes to such a degree as Venus or Jupiter, but it undergoes a change of magnitude in proportion to distance from the earth. Consequently, Mars in its evening rising seems to equal the star of Jupiter in magnitude, so that except for fiery brightness it is not set apart. But in its approach [to the Sun] and concealment it can scarcely be distinguished from stars of the second magnitude. It follows that it comes near to the earth in its evening rising, but in morning it withdraws to the greatest distance, which certainly cannot happen in any way by reason of an epicycle. Therefore, for the

[2] Pliny, *Natural History*, II:14 (given by Rheticus as 2:17 according to an alternate numbering).

motions of Mars and the other planets to be put aright, it is clear that another place is to be assigned to the earth.

Fourth, my teacher saw that only from this rule can it come to be appropriately that all revolutions of circles in the world are moved equally and regularly about their own centers and not those of others, which is most greatly characteristic of circular motion.

Fifth, it is to be established with Mathematicians no less than with Physicians, what Galen insisted upon here and there, "Nature does nothing without purpose," and "So wise is our maker that each of his works has not one use, but two or three or often more."[3] Wherefore, when we see that seemingly endless appearances are satisfied by this one motion of the earth, should we not grant to God, contriver of nature, that industry that we perceive common Makers of clocks to have? They take care most zealously lest they incorporate any gear which may be superfluous or else another, a small interchange of which may complete it in a more suitable fashion by having been shifted in position. But what might have influenced my teacher that he should not assume, as a Mathematician, an appropriate rule of the motion of the terrene globe? Since he saw that for a certain doctrine of celestial things to be established, with the adoption of such hypotheses, it suffices for us to have a single and immobile eighth sphere with the Sun immobile in the center of the Universe; and an epicycle on eccentric, or an eccentric on an eccentric, or an epicycle on an epicycle suffices even with regard to the motion of the remaining planets.

He assented to these things because the motion of the earth in its own orb brings

[3] Rheticus gives these quotations in Greek. I have taken the translations from Rosen, *Three Copernican Treatises*, 137 n. 118, where the source is identified as Galen, *De usu partium* 10.14.

about the arguments of all the planets except the Moon.[4] One single motion may seem to be the cause of all diversity, which indeed clearly manifests in the three superior planets at a distance from the Sun, in Venus and Mercury on the other hand near the Sun, and further it produces this motion: namely, that there may be satisfied at least by a single deviation in latitude of the deferent of the planets, of any of the planets. And thus the motions of the planets, chiefly, demand hypotheses of such kinds.

Sixth and last, this thing most greatly moves my teacher, because he saw that the principal cause of every uncertainty in astronomy was that the makers of this doctrine (but I wish a word of forgiveness of divine Ptolemy the Father of Astronomy) did not measure their own Theories and accounts of the motion of celestial bodies to be emended severely enough by that rule, which admonishes that the order and motions of the celestial orbs be consistent with a most perfect system. So that we may very greatly grant their honor to them (as is fair), nevertheless indeed it is to be wished that, in having established the harmony of motions, they might have imitated Musicians who, with one chord having been tightened or loosened, when the greatest care and diligence has been applied for a long time, they form and adjust the sounds of all the rest, until they bring the desired harmony all together and there is no dissonance observed in any of them. If this, as I say meanwhile about Al-Battānī, had been followed in his own Work, without doubt today we would have a more certain account of all motions. Indeed, it is probable that the Alfonsine Tables have selected the most from him, and since the single rule sometimes

[4] The *true argument* is “the arc of an epicycle leading from the true aux to the center of the planet.” “*Argumentum verum* dicitur arcus epicicli cadens inter augem veram et centrum planetae,” in Olaf Pedersen, “A Fifteenth Century Glossary of Astronomical Terms,” *Classica et Mediaevalia* 9 (1973): 591, entry 58 (my translation). Rheticus means that terrestrial motion causes the apparent inequalities attributed to epicycles.

has been neglected, if only the soul confesses truth, the ruin of all astronomy may be feared.

In the common principles of astronomy, truly one could see that all celestial appearances direct themselves to the mean motion of the Sun, and all harmony of celestial motions is established and preserved in conformance with its government. Whence also by the Ancients the Sun was called *xorogos* [choral leader], governor of nature, and King. But in what way may it conduct the administration: just as God governs this whole universe? as Aristotle most admirably described in *peri cosmou*,[5] or whether truly it acts as God's administrator in nature itself by passing through all of heaven, and not resting in place at all, does not yet seem to be wholly explained or perfected. However, which of the two of these may be adopted as preferable, I leave to be determined by Geometers and Philosophers (who truly may be imbued with mathematics). Since in the appraisal and division of this kind of controversy, the opinion is to be carried not from plausible opinions, but from mathematical laws (in the court of which this cause is heard). The former means of governing [heliocentrism] is cast aside, the latter [geocentrism] retained. But my teacher came to the opinion that the condemned rule of government of the Sun in the nature of things is to be called back, yet in such a way indeed that the received and approved rule retains its own place. For he sees that neither is the work in human matters such that the Emperor himself travels through cities one at a time, whereby at last he performs the duties laid on him by God; nor does the heart travel to the head or the feet or other parts on account of the preservation of living beings, but through other organs, appointed in this by God, it presides over its own duty.

[5] Rosen, *Three Copernican Treatises*, 139, identifies the book as the pseudo-Aristotelian *De mundo*.

Then, when he decided that it was proper for the mean motion of the Sun to be such a kind of motion, which is based not so much upon imagination, as indeed in the remaining planets, but it has a cause per se, when it shows itself to be most truly “both choral dancer and choral leader,”[6] it is a fact that his firm opinion does not prove things opposed to truth. For through his hypotheses he realized that the efficient cause of the equal motion of the Sun can be geometrically deduced and demonstrated, because that mean motion of the Sun may be detected necessarily in all the motions and appearances of the remaining planets by a certain rule, as it appears in each; and consequently a certain doctrine of celestial things makes manifest motion of the earth in an eccentric, in which nothing is to be changed without at the same time the whole system, as was fitting, being replaced from new in rules that ought to occur. Since we cannot suspect the government of this kind of Sun in the nature of things from our common theories, and for the most part, however, we neglected the Sun’s *egcomia* [praises] of the Ancients as poetry. And so you see thus, what kind of hypotheses for saving motions it was proper for my teacher to assume when these things had been established thus.

[6] Rheticus gives the phrase in Greek. I have taken the translation from Rosen, *Three Copernican Treatises*, 139.

APPENDIX FIVE

ERASMUS REINHOLD'S COMMENTARY ON PEURBACH'S *THEORICAE NOVAE PLANETARUM* (1543 AND 1553): SELECTED PASSAGES WITH TRANSLATION

Unlike the primary sources I have translated in other appendices, Reinhold's commentaries on the *Theoricae novae* are not available in a modern edition. For reference, I have included a transcription of the original Latin with my translation.

Wittenberg, 1542

Early reference to Copernicus; from Reinhold's preface to the reader, fol. C7r.

Tametsi uideo quendam recentiorem praestantissimam artificem, qui magnam de se apud omnes concitauit expectationem restituendae Astronomiae, & iam adornat aeditionem suorum laborum, sicut in alijs Astronomiae partibus, ita etiam in hac uarietate motus Lunae explicanda *dis diaoasom*[1] dissentire a forma Ptolemaica. Tribuit enim Lunae epicyclum epicycli, quo posito, quia necesse est Lunam alias propiorem fieri centro primi epicycli, alias ab eodem remotiorem. . . .

Although, I perceive a certain more recent person, a very eminent author, who has produced among all a great expectation of the restoration of Astronomy from him. And now he is publishing an edition of his labors that, just as in other parts of Astronomy, so

[1] My transcription of the Greek phrase is a best guess. Roughly, the reference is to phases of the Moon; compare the oft-quoted English translation in Duhem, *To Save the Phenomena*, 72.

also in this variety explaining the motion of the Moon *dis diaoasom*, differs from the Ptolemaic form. Namely, he assigns to the Moon an epicycle of an epicycle, on which it is placed, because it is necessary that the Moon at one time become closer to the center of the first epicycle, at another time more remote from it. . . .

Early reference to Copernicus; from the motion of the eighth sphere, fol. e2v-e3r.[2]

Est uero & hoc sciendum, Ptolemaeum in motu octauae sphaerae haec duo considerare, progressus stellarum fixarum, deinde & apogiorum planetarum. Recentiores autem plura adijcere coacti sunt obseruationibus, quibus explorabant apogia & stellas fixas non tantum progredi, idque inaequaliter, Verum etiam mutari diurnitate temporis anni quantitatem[3], & maximas solis declinationes. Quare longe aliam rationem motus octauae sphaerae susceperunt, ut earum apparentiarum caussas monstrare possent, quae tamen ratio haudquaquam cum obseruationibus congruit. Itaque cum hae artes iam diu desiderent aliquem Ptolemaeum, qui labentes disciplinas restituat, ac in uiam reuocet, spero eum nobis tandem ex Prussia obtigisse, cuius diuinam ingenium tota posteritas non immerito admirabitur, Verum denuo audiamus Purbacchium tradentem non Ptolemaica, sed Alphonsinorum & Thebitij dogmata.

And truly this is to be understood, that Ptolemy in the motion of the eighth sphere considers these two things: the advance of the fixed stars [i.e., precession], and then the advance of the apogees of the planets. However, more recent [astronomers] have been

[2] The slightly obscured signatures in the copy I examined (History of Science Collections, University of Oklahoma) appear to be mislabeled as signature c, but they follow signatures c and d.

[3] Corrected from *quantiatem*.

constrained by observations to add more things as support, with which they established not only that the apogees and fixed stars advance--and what is more [they do so] unequally--also, indeed, [they established] that the amount of days in the period of the year changes, and the maximum declinations of the sun. Wherefore for a long time they accepted another rule of the motion of the eighth sphere, so that they could show the causes of their appearances; which rule nevertheless corresponds not at all with observations. Therefore, since these arts for a long time now have been longing for some great Ptolemy, who might restore the tottering disciplines and bring them back to the path, I hope that he has come to us at last from Prussia: [one] whose divine genius all posterity not undeservedly will admire. Indeed we may hear anew Peurbach teaching, not Ptolemaic doctrine, but that of the Alfonsine [Tables] and of Thābit [ibn-Qurra].

Wittenberg, 1553

Cosmology and physics; from the commentary on the Sun, fol. 26v-27v.

Orbis supremus est. E.

Infimus orbis. C.

Tertius & medius orbis, ad cuius motum sol incedit sub ecliptica est. D.

B. Centrum est mundi, super quo descripta est & extrema circumferentia supremi orbis, quae hic representat superficiem conuexam eiusdem orbis, & intima circumferentia infimi orbis representans superficiem concauam eiusdem.

A. Centrum eccentrici orbis, super quo ambae extremitates medij orbis, exterior & interior describuntur. Exterior seu remotior a centro designat tam superficiem conuexam huius medij orbis, quam concauam supremi. Interior autem superficiem concauam eiusdem medij & conuexam infimi. Sunt enim & hi & alij coelestes orbes inter se contigui, id est, eorum ultima seu extrema simul sunt, seu ita sese contingunt, ut nihil possit esse medium.

Orbem Cicero & alij tantum etiam pro circulo dixerunt. Sed hoc loco significat sphaeram sic excauatam, ut intra se aliam recipiat contiguam. Cuius rei exemplum qualecunque uidere licet in partibus oui, ubi primum crusta exterior includit omnia interiora, inde exigua uel tenuis tunica seu membrana continet proximum liquorem, quem uocant albumen. In medio est uitellus tanquam terrea pars oui. Martialis. Candida si croceos circumfluit unda uitellos. Aliquod etiam exemplum pingunt caeparum tunicae multiplices, ubi semper interiores ac medio propriores sunt angustiores.

Est autem Aristotelicum coelestia corpora lucida non ferri motu proprio seu progressionis, ut animalia, sed motu uectionis. Non enim ut pisces in aquis, uel aues in aere temere uagantur hunc illuc, sed perpetua ac legitima aequalibilitate ac intra certas metas circumferuntur. De qua re ipsum Aristoteles legant studiosi libro 2 de coelo. Vbi etiam monet duplicem sphaerae motum per se esse *kulisin kai dinesin* uolutationem & conuersionem, ac docet coeli motum esse *dinesim* non *kulisim*, quia semper eadem duo puncta manent immobilia.

The highest orb is E.[4]

The lowest orb [is] C.

The third and middle orb, by the motions of which the sun proceeds under the ecliptic, is D.

B is the center of the world, around which is drawn both the outermost circumference of the highest orb, which here represents the convex surface of the same orb, and the innermost circumference of the lowest orb representing the concave surface of the same.

A [is] the center of the eccentric orb, around which are drawn both extremes of the middle orb, the outer and the inner. The outer or more distant from the center indicates the convex surface of this middle orb which is like the concave [surface] of the highest. And the inner surface of the same middle [orb] is like the convex [surface] of the lowest. Both these and other celestial orbs are contiguous among themselves, that is, the farthest of them are at the same time the highest, or else they touch each other in such a way that nothing can be between [them].[5]

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[4] The diagram Reinhold explains is reproduced as figure 3 of this dissertation.

[5] Up to this point, the commentary repeats the 1542 edition. The rest of the passage is new to the 1553 edition.

Certainly Cicero and others only said *orbis* for circle. But in this place it signifies a sphere thus hollowed out so that it can receive another contiguous within itself. One can see an example of such a thing in the parts of an egg, where the first outer shell encloses all inner things, then the scant or thin covering or membrane contains the liquid next, which is called the white. In the middle is the yolk as the earthly part of the egg. Martialis. The white parts like water encompass the yellow yolks. The manifold layers of onions represent yet another example, where the inner [layers] and the ones closer to the middle are always more confined.

Moreover it is Aristotelian that the bright celestial bodies are not borne by their own motion or [the motion] of an advance, as living beings [are], but by a motion of carrying. They do not randomly wander hither and thither as fish in water or birds in air, but they are carried around by a perpetual and lawful uniformity and within set boundaries. About which things the studious may read Aristotle himself in *De caelo* Book 2. Where, moreover, he states with authority that the double motion of the sphere by itself is rolling and revolving. And he teaches that the motion of the heavens is revolving not rolling because the same two points always remain immobile.

Background to the second edition; from the commentary on the Sun, fol. 57r.

Superior pars huius operis ab autore Erasmo Reinhold in hac editione emendata, & magna ex parte de nouo scripta est, ut fuit in eo mirifica diligentia, & saepe recitabat hoc ipsum *deutero phrontides sophoterai*. Edita autem hac noua parte operis, mors Erasmi abrupit inchoaram emendationem, ut & alias multas lucubrationes, quae si perfici potuissent, multum profuturae erant posteritati. Inchoauerat Erasmus sequentium annorum Ephemeridas, Tabulas Eclipsium, explicationem demonstrationum Copernici, & alia quaedam utilia monumenta, quae, si uitae spatium aliquanto longuis ei contigisset, absoluere decreuerat. Eo magis autem deploranda est mors eius, quia pauci Mathematum studia colunt, & multo pauciores adiuuant discentes. Ac nisi diuinitus in aliquibus ingenijs cura accendetur & discendi & conseruandi has artes, aliquanto post etiam anni spatia ignota erunt. Adhortandi sunt autem & sapientes Gubernatores & Scholastici harum artium amantes, ut & ipsi propter gloriam Dei ac propter communem utilitatem Ecclesiae his studijs opem ferant.

Vt autem in manibus discentium sit hic Libellus Theoricarum illustratus ab Erasmo, post eius mortem edita est pars sequens, sumpta ex priore eius editione. Etsi enim autor si pertexuisset emendationem, quasdam materias magis illustrasset, tamen haec prima editio etiam prodest discentibus. Curauit autem Caspar Peucerus, ut haec postrema pars incorrupta ederetur. Anno 1553.

The above part of this work was emended by the author Erasmus Reinhold in this edition, and in great part written anew, as there was wonderful diligence in it, and often he read out this thing itself *deutero phrontides sophoterai*. However, after this new part of the work had been completed, the death of Erasmus broke off the incomplete emendation, along with many other works composed by night, which, if they could have been completed, would have been greatly useful for posterity. Erasmus had begun Ephemerides of following years, Tables of Eclipses, an explanation of the demonstrations of Copernicus, and certain other useful monuments, which, if a somewhat longer space of life had befallen him, he would have decreased by completing them. Moreover his death is to be lamented all the more, because few cultivate the studies of Mathematics, and fewer by far assist its learning. And unless by divine influence in some geniuses the care for learning and preserving these arts is entered upon, still after some moderate space of years they will be unknown. Now the wise Governors and Scholastics loving these arts ought to be urged to bring about themselves the power to aid these arts, both on account of the glory of God and because of the common utility of the Church.

But so that this Little Book of Theoricas made clear by Erasmus might be in the hands of those who are learning, after his death the following part has been published, taken from his earlier edition. And even if the author would have completed the emendations and made certain subject matters more clear, nevertheless this first edition is still beneficial to learning. Moreover Caspar Peucer attended to it, in order that this last part might be published uncorrupted. In the year 1553.

APPENDIX SIX

COSMIC SIZES AND DISTANCES ACCORDING TO CASPAR PEUCER

Peucer gives sizes and distances for the celestial bodies and the Earth in *Elementa doctrinae de circulis coelestibus* (1569), pages 73-77 and 82-86. Distances are given in Earth radii (e.r.). Changes in eccentricities are based on a ratio where the diameter of the planet's deferent equals 60. As a rule, Peucer does not indicate the beginning and end-points of changes in eccentricity; I have included the changes with the last authority given for distances. Diameters and volumes are in units where the Earth equals one or as a ratio to the size of the Earth. Some of Peucer's values are approximate.

Planetary distances from the center of the world

	Minimum	Maximum	Eccentricity
Fixed Stars	20,081;30	-----	-----
Saturn	14,378;20	20,072;15	-----
Jupiter	8,853;45	14,369;15	-----
Mars (Ptolemy)	1,216	8,840	-----
Mars (Al-Battānī)	1,176	8,022	decrease of 0;42
Sun (Ptolemy)	1,120	1,210	2;30
Sun (modern)	-----	1,179	1;56
Venus	167;57	1,115;3	-----
Venus (Al-Battānī)	166	1,070	change of 1/5
Mercury	56 64;10 (Ptolemy)	167;29 166 (Al- Battānī)	-----
Moon at syzygy (Ptolemy)	55;8	64;10	-----
Moon at syzygy (More recent)	-----	65;30	-----
Sun-Moon gap	Ptolemy: 1,146 Recent: 1,114	-----	-----
Axis of Shadow	Ptolemy: 274 Recent: 265	-----	-----
Elementary Sphere	52;17	-----	-----

Diameters and volumes of cosmic bodies

	Diameter	Volume
Saturn	4 1/2 (9:2)	90 1/8
Jupiter	4 4/7 (32:7)	95 1/2
Mars	7:6	1 1/3
Sun (Ptolemy)	5 1/2	166 3/8
Sun (Copernicus)	5;27	162 - 1/8
Venus	3:10	28:37
Mercury	-----	1/22,000 Al-Battānī: 1/19,000
Moon	5:17	Ptolemy: 1 in 39 2/3
Moon (Copernicus)	2:7	1 in 43 - 1/8
Earth	radius: ca. 860 milliaria	-----

APPENDIX SEVEN

COSMIC SIZES AND DISTANCES ACCORDING TO MICHAEL MAESTLIN'S *EPITOME ASTRONOMIAE* (1610)

Maestlin's values for sizes and distances come from the *Epitome astronomiae* (1610), most from the appendix on cosmic measurements but also scattered throughout the last book. Most celestial distances are given in Earth radii (e.r.). In some cases, Maestlin has calculated the distance in German miles that a point on a sphere's equator would travel in a single pulse (1/4,000 of an hour); I have included these values under eccentricity since they apply only to concentric orbs. Information on eccentricity includes both the eccentricity *E* (where the diameter of the deferent equals 60 units) and the distance from the center to the eccenter *D* (given in e.r.). Diameters and volumes are given in units where the Earth equals one. I have added a list of units of measurements drawn from the *Epitome*. Authorities are those cited by Maestlin. The values he ascribes to past astronomers do not necessarily correspond to the historical record, and he often rounds off results for convenience. He attributes most of his figures to al- Farghānī, so all values are ascribed to this authority except where noted.

Planetary distances from the center of the world in a geocentric system

	Minimum	Maximum	Eccentricity/Pulse
Ninth Sphere	over 45,000 (probably Reinhold)	-----	1 pulse: 2,528 miles
Fixed Stars	Al-Farghānī: 20,110 More accurate: ca. 22,000-25,000 Tycho: ca. 13,000-14,000	-----	1 pulse: 1,132 miles ----- 1 pulse: 732-788 miles
Saturn	14,405	20,110	-----
Jupiter	8,876	14,405	-----
Mars	1,220	8,876	-----
Sun	Al-Farghānī: 1,120	Al-Farghānī: 1,220 Ptolemy: 1,210	-----
Sun (Copernicus)	Radius of eccentric sphere: 1,142		
Sun (C): Max Eccentricity	1,094	1,190	E: 2;30,7 D: 48 e.r.
Sun (C): Min Eccentricity	1,105	1,179	E: 1;55,53 D: 37 e.r.
Venus	167	1,220	-----
Mercury	64;10	167	-----
Moon	33;33[1]	64;10	-----
Moon (Ptolemy)	Syzygy: 53;50 Quadrature: 33;33	Syzygy: 64;10 Quadrature: 43;53	-----
Moon (Copernicus)	Syzygy: 55;8 Quadrature: 52;17	Syzygy: 65;30 Quadrature: 68;20	-----
Axis of Shadow	268 Copernicus: 265	-----	-----

[1] Al-Farghānī's minimum lunar distance should be 32;33; Van Helden, *Measuring the Universe*, 30.

Planetary diameters and volumes

	Diameter	**Volume**
Sun (Ptolemy)	5;30 (11:2)	166 (1,331:8)
Sun (Copernicus)	5;27	162 - 1/8
Earth to Moon (Ptolemy)	17 4/5:1	39 (4,913:125)
Earth to Moon (Copernicus)	7:2	-----

Units of measurement:

1 German mile = 4 Italian miles (approximate)
1 Italian mile = 8 stadia or 1,000 paces[2]
1 Arabic mile (?) = 4,000 cubits[3]
1 stadium = 125 Roman paces
1 pace = 5 feet
1 foot = 4 palms or 1 spithamen and a palm
1 spithamen = 3 palms
1 palm = 4 digits
1 digit = 4 barleycorns

[2] Maestlin explains (p. 85) that the Italian mile received its name because it contains a thousand (*mille*) paces.

[3] Where 1 cubit = 6 palms, or 24 fingerbreadths according to Van Helden, *Measuring the Universe*, 30-31.