Filozofski vestnik Volume/Letnik XXV • Number/Številka 2 • 2004 • 143–166

COPERNICUS' FIRST FRIENDS: PHYSICAL COPERNICANISM FROM 1543 TO 1610

Katherine A. Tredwell and Peter Barker

Early assessments of the Copernican Revolution were hampered by the failure to understand the nature of astronomy in the sixteenth century, as scholars took statements made in praise of Copernicus to be implicit endorsements of his heliocentric cosmology. Gradually this view has been supplanted by the acknowledgement that many supposed partisans of Copernicus only endorsed the use of his astronomical models for the calculation of apparent planetary positions, while rejecting or remaining silent on the reality of heliocentrism. A classic example of this shift in historiography concerns Erasmus Reinhold (1511–1553), a professor of mathematics at the University of Wittenberg. Reinhold's use of Copernican models in his *Prutenic Tables* (*Tabulae prutenicae,* 1551) has led to the mistaken belief that he sanctioned a Sun-centered cosmology as well. Careful reassessment of his published writings has revealed that he commended certain aspects of Copernicus' work, such as the elimination of the equant, but showed no interest in heliocentrism (Westman, 1975: pp. 174–178). Other supposed Copernicans, such as Robert Recorde (c. 1510–1558), expressed some openness to the Earth's motion but left no clear indication of what they thought to be the true system of the world (Russell, 1972: pp. 189–191).

Between the publication of Copernicus' epoch-making book *On the Revolutions of the Celestial Orbs* (*De revolutionibus orbium coelestium*) in 1543 and the year 1610, only a handful of individuals can be identified with certainty as Copernicans, in the sense that they considered heliocentrism to be physically real and not merely a calculational convenience. In this paper we discuss this tiny group of true Copernicans and their reasons for believing that Copernicus, not Ptolemy or Tycho Brahe, was correct. Most expressed their convictions in terms familiar to their contemporaries. For instance, they thought of the motions of the planets in terms of three-dimensional orbs or two-dimensional circles which defined the direction to the planet for an observer on the Earth, measured from some fixed line of reference. They did not think of planetary motions as continuous paths through space. Not until the seventeenth century did Copernicanism in the modern sense begin to appear, after the publications of Johannes Kepler's *New Astronomy* (*Astronomia nova,* 1609) and Galileo Galilei's *Sidereal Messenger* (*Sidereus Nuncius,* 1610) introduced new factors to the cosmological debate.

We take as our starting point the list of Copernicans before 1600 identified by historian of science Robert S. Westman: Georg Joachim Rheticus, Michael Maestlin, Christopher Rothmann, Johannes Kepler, Giordano Bruno, Galileo Galilei, Thomas Digges, Thomas Harriot, Diego de Zúñiga, and Simon Stevin (Westman, 1980: p. 136 n. 6). Two other figures will also be discussed in the paper. Gemma Frisius preferred the Copernican system to its Ptolemaic rival as a description of the true arrangement of the world. William Gilbert never endorsed heliocentrism explicitly, but he was favorably inclined towards Copernicus and accepted that the Earth rotated daily on its axis. He is included as a probable Copernican. One conspicuous absence is Thomas Harriot, whose astronomical works were not published and today are scattered among several manuscript collections. Possibly a very small number of Copernicans in the period up to 1610 have not been identified, so our list should not be regarded as exhaustive. However, the positions we discuss in this paper reflect the beliefs of a majority of early heliocentrists. We begin at the beginning, with the first followers of Copernicus.

1.

Georg Joachim Rheticus (1514–1574) was a professor of mathematics at Wittenberg, then in Leipzig; later, he studied medicine in Prague and became a physician in Cracow (Burmeister, 1967–68). In 1539, during a leave of absence from his position at Wittenberg, Rheticus visited Copernicus at his home in North Prussia. How much he had already heard of Copernicus is uncertain, but once in Frauenberg he became persuaded that his host's work offered many advantages over Ptolemy. Quickly he wrote a nontechnical treatise on the new astronomy, the *First Account* (*Narratio prima,* 1540), explaining Copernicus' models. This became the first printed description of Copernican heliocentrism. Soon after, he supervised the process of publishing *On the Revolutions,* but left the task to be finished by Andreas Osiander and Ioannes Petreius so that he could move from Wittenberg to Leipzig (Barker and Goldstein, 2003).

The *First Account* described many features of Copernican astronomy. Some, such as the new determination of the distances of the Sun and Moon from the Earth and the elimination of the equant, were compatible with geocentrism and therefore received positive attention from many sixteenth-century astronomers (Rheticus, 1971/1540: pp. 133, 135). But today the book is remembered chiefly for its identification of many advantages of heliocentrism over geocentrism. Its list may serve as a useful starting-point for our discussion of sixteenth-century Copernicanism.

Rheticus gives many reasons for accepting Copernicus over geocentric astronomy. Copernicus explains the motions of precession and the changing obliquity of the ecliptic by the motion of the Earth. The changing apparent eccentricity of the Sun appears in the eccentricity of the other planets. The centers of the planetary deferents seem to be near the Sun. Mars, for instance, has a parallax sometimes greater and sometimes less than the parallax of the Sun, so the Earth cannot be its center of motion. All circles have their own centers as their centers of motion, which eliminates the equant (though this did not require heliocentrism as Rheticus implied). Copernicus uses terrestrial motion to explain many inequalities of motion, so that one motion has multiple purposes. Geocentrism related many motions to the motion of the Sun, but heliocentrism creates harmony by linking a variety of inequalities to terrestrial motion as befits God's skill as Creator. For example, Copernicus explains, as Ptolemy cannot, why planetary stations and retrogradations are linked to the Sun; they are illusions created by the annual motion of the Earth on the Great Orb (Rheticus, 1971: 136–140 and passim).

Rheticus also pointed out that Copernicus eliminated the invention of invisible spheres beyond the sphere of fixed stars (used by geocentrists to explain daily rotation and other motions) by attributing all motions to the Earth instead. Furthermore, heliocentrism created a qualitative distance-velocity relation in which the largest planetary spheres were slowest and the smallest spheres were fastest (Rheticus, 1971: pp. 144–146). Finding a distance-velocity relationship may have motivated Copernicus to investigate heliocentrism (Goldstein, 2002). The motion of the Earth explains the bounded elongation of Mercury and Venus, and the motions of all planets in latitude. Rheticus stressed two advantages that he evidently found most convincing. First, in contrast to daily rotation and other terrestrial motions which could be attributed to the heavens, he could not see a way to reconcile precession to geocentrism. Second, he was impressed that heliocentrism created a harmony of interconnected motions and cited harmony more frequently than did Copernicus (Westman, 1975: p. 185). At the same time he stated in the *First Account* that he would leave it to mathematicians and philosophers to determine which of the two systems was correct. Rheticus did not write further in defense of heliocentrism. Perhaps he concluded on further reflection that the advantages of

Copernicanism did not prove beyond doubt that the Earth moved, though this must remain speculation given the current state of evidence.

2.

Gemma Frisius (1508–55) began his career as a mathematical practitioner, and made significant contributions to geography, but spent his later years practicing and teaching medicine at Louvain (Kish, 1967; Lammens, 2002). Gemma may have heard about Copernicus' theories even before their publication . He was briefly a client of Johann Flaschbinder (known from the place of his birth by the Latin name "Dantiscus") who later became Bishop of Ermland and Copernicus' superior. However, Gemma received a copy of the *First Account*, probably in 1540, and later made extensive annotations in a copy of *On the Revolutions* (Lammens, 2002: i: pp. 60–4 and ii, passim.).

In addition to praising Copernicus in letters written to Dantiscus in the early 1540s, Gemma endorsed physical Copernicanism in a 1555 letter published as a preface to an astronomical work by Ioannes Stadius (Gemma Frisius, 1555). He notes the increased accuracy of Copernican calculations, for example in determining the time of the equinox. Gemma then argues that Copernicus can explain things that Ptolemy can only assume, for example that the superior planets are always at the perigee of their epicycles (and hence in the middle of a retrogression) when they are diametrically opposite to the Sun in the sky. Gemma describes Copernicus' result as a demonstration of the true causes of the phenomenon (Gemma Frisius, 1555: fol. a 2 v). This is an unusual and strong claim. Although demonstration of the true cause of a phenomenon, according to the standards established by Aristotle in the *Posterior Analytics*, was an ideal in all areas of natural philosophy, this standard was generally held to be unobtainable in astronomy (Barker and Goldstein, 1998; Barker, 2000a, p. 80). Gemma not only asserts the physical reality of Copernicus' cosmic scheme but claims that it provides scientific explanations of previously unexplained facts according to the highest standards accepted at the time.

3.

Most early readers of Copernicus with the mathematical competence to appreciate his technical innovations nevertheless did not accept heliocentrism as a statement of physical reality. Reinhold, Rheticus' senior colleague at Wittenberg, figured prominently in the promotion of *On the Revolutions* because he prepared the *Prutenic Tables* (1551) based on Copernican astronomical models. Yet he never advocated a Sun-centered system and the aspects of Copernicus in which he took an interest, such as his lunar theory, did not require any motion of the Earth (Reinhold, 1542: fol. C 7 r). Reinhold was one of a group of mathematicians at Wittenberg during the sixteenth century who considered Copernican astronomy useful for the calculation of apparent planetary positions but physically objectionable, an attitude Westman has termed the "Wittenberg Interpretation of Copernicus" (Westman, 1975). Reinhold's successor Caspar Peucer (1525–1602) wrote a textbook of astronomy incorporating Copernicus' determination of the distances of the Sun and Moon as well as arguments upholding the centrality and immobility of the Earth on mathematical, physical, and religious grounds (Peucer, 1569: pp. 75–76, 100–107).

Reinhold and Peucer were among the students at Wittenberg who were encouraged to study mathematics by Philip Melanchthon (1497–1560), a Lutheran reformer who saw the certainty of mathematical astronomy as an unambiguous sign of providential design. Through his students, Melanchthon's influence was passed on to later generations of Lutheran mathematicians, including Michael Maestlin and Tycho Brahe (1546–1601). Tycho, who studied briefly at Wittenberg and was acquainted with Peucer, transformed Copernicus' heliocentric system into the geostatic system called "Tychonic": the Moon, Sun, and fixed stars circle the unmoving Earth, while the five planets circle the moving Sun. His system incorporated many advantages of heliocentrism, such as the bounded elongations of the inferior planets, while avoiding the difficulties of terrestrial motion. However, the distances of the celestial bodies required that the deferents of the Sun and Mars overlap, which would be impossible if the planets were carried by impenetrable orbs. Tycho overcame this difficulty by arguing that the heavens were composed of a fluid material, an idea that may have been suggested to him by a Copernican.

4.

Christopher Rothmann (born ca. 1560, d. before 1611) was educated, like Rheticus, at Wittenberg, where he studied theology, mathematics and astronomy. During the 1580s he served as *mathematicus* to Wilhelm IV, Landgraf of Hesse (1532–92). At court in Kassel he assisted the Landgraf in a program of systematic astronomical observation, corresponded with Tycho Brahe and wrote several books which remained unpublished at his death (Barker, 2000c). These included a handbook of astronomy in which he attempts to reconcile scripture with the abolition of celestial spheres (Rothmann, 2003/1589), and a book on the comet of 1585, which may have persuaded Brahe that the substance of the heavens was a fluid like air, through which the planets moved themselves (Goldstein and Barker, 1995). His endorsement of Copernicus occurs in correspondence published by Brahe in 1596, after Rothmann had visited Hven, and according to Brahe, recanted. Recent evidence suggests that Rothmann endorsed a geo-heliocentric position, rather than heliocentrism, around 1590 (Barker, 2004). Rothmann subsequently dropped out of sight and his final views are unknown, but, at least in a letter dated October 1588, he asserts the truth of the Copernican doctrine on the grounds that Copernicus not only shows that stations and retrogradations occur in positions linked to the positions of the Sun, but also shows why they occur there. In other words, Copernicus demonstrates, or explains, features of planetary motion that are described but not explained by Ptolemy. This is the same methodological argument for Copernicanism made by Gemma Frisius.

5.

Michael Maestlin (1550–1631) studied mathematics and theology (Barker, 2000b; Rosen, 1974). Save for a brief period as a pastor in Backnang (1577–1580) and a professor at Heidelberg (1580–1584), he spent his life teaching mathematics at Tübingen. From the nova of 1572 and the comets of 1577 and 1580 he concluded that these phenomena were beyond the Moon, contradicting the Aristotelian doctrine of an unchanging celestial realm. He entertained heliocentrism in an early work on the nova but did not become a committed Copernican until his work on the comet of 1577 (Westman, 1972). Maestlin calculated that the path of the comet would require it to pass through celestial orbs in the Ptolemaic system, an impossibility according to the reigning physics of the day. However, in the Copernican system the comet would be located on its own orb in the gap between the spheres of Venus and the Earth. He announced this discovery and his support of Copernicanism in *Observation and Demonstration of an Aethereal Comet* (1578) and did similar work on the comet of 1580 in *Astronomical Consideration and Observation of an Aethereal Comet* (Maestlin, 1578: pp. 38–39; Maestlin, 1581; Barker and Goldstein, 2001: pp. 93–95). In the classroom, Maestlin continued to teach old-fashioned Ptolemaic astronomy including the use of equants, but he also taught the Copernican system to some of his students (Methuen, 1996). In later editions of his textbook *An Epitome of Astronomy* (1610, 1624) he added a passage ridiculing geocentrism and geoheliocentrism and upholding heliocentrism as the best alternative (Tredwell, 2004).

When Kepler, Maestlin's most famous student, published his first book

Mystery of the Cosmos (1596), Maestlin on his own initiative added two other works to be included in the volume. One, an appendix written by Maestlin, explicated the sizes of the orbs and distances of the planets according to Copernican values. This appendix demonstrates his understanding that the apparatus of orbs for each planet extended further than the inner and outer boundaries defined by the three-dimensional motion of the planet itself (Grafton, 1973). Maestlin also added an extensively annotated new edition of the *First Account.* In the commentary he calculated the distance that a star must travel in a single second (1200 German miles) due to the daily rotation of the heavens in a geocentric system. Maestlin argued that the incredibly swift motion of such an immense sphere is far more absurd than the daily rotation of the comparatively tiny Earth. In the 1621 edition, and in the supplement to the *Epitome* mentioned above, he extended the argument to include the Tychonic system. He also appealed to the power of an omnipotent God to overcome objections to the Copernican system involving the size of the sphere of fixed stars and the unused space between Saturn and the sphere of stars (Tredwell, 2004).

6.

Simon Stevin (c.1548–c.1620) was a mathematical practitioner born at Bruges in the Netherlands. After 1584 he served as mathematical tutor to Maurice of Nassua, Prince of Orange. Stevin defended physical Copernicanism in the third book of his *Mathematical Memoirs*, composed to instruct the prince in astronomy and cosmology, and published between 1605 and 1608. Although this falls right at the end of our period, barely predating the publication of Kepler's *New Astronomy* and Galileo's *Sidereal Messenger*, the book probably records opinions developed before 1600 while Stevin was instructing the prince.

Stevin's main arguments for Copernicanism are by now familiar, although he is unusually concerned with their physical interpretation.

Following Rheticus, and Brahe, Stevin believes that observations made at two different times of the year may be used to directly establish the distance to an outer planet, "for the distance between two positions which the Earth has at different locations in its path serves us as the base of a triangle, whose ratio to the sides is very perceptible, …"(Stevin, 1961: p. 124,) Both Rheticus and Tycho asserted that in the case of Mars such a measurement would demonstrate that a geocentric system was untenable. Stevin merely concludes that such measurements support the Copernican order of the world.

A major argument is the correlation between distances and velocities that exists in Copernicus' system but is absent in Ptolemy's. The most striking manifestation is the sphere of fixed stars, which being furthest from the center ought to move most slowly, but in Ptolemaic astronomy is made to move most swiftly of all celestial spheres, revolving around the Earth in 24 hours: "It is more in accordance with reason to believe and to assume that this fastest motion is to be assigned to the smallest circle, to wit, the circle of the Earth in its place" (Stevin, 1961: p. 125, tr. Dikshoorn), that is its rotation about its own axis. This, as we have seen, is a variant on Copernicus' main argument for his system, and similar arguments appear in Rheticus and Maestlin.

Like Copernicus, Stevin enumerates the resources of heliocentrism in explaining the connection between the motions attributed to the planets' epicycles in Ptolemaic astronomy and the motion of the Sun, also showing, for example, why outer planets are nearest the Earth at conjunction and furthest at opposition (Stevin, 1961: p. 139). Initially he emphasizes the economy of the Copernican model: the motion of the Earth eliminates the epicycles in Ptolemy's planetary models (Stevin, 1961: pp. 123–5). Stevin also suggests that it is implausible to believe that the sphere of fixed stars moves in one direction while all of the planets (at least in their proper motions) move in the other. This arrangement, which offends natural reason, can again be avoided by endowing the Earth with a daily rotation (Stevin, 1961: p. 125).

However, Stevin does not accept Copernicus' system uncritically. In particular he rejects the alleged third motion of the Earth (the rotation by means of which the axis maintains a fixed direction in space). An early adherent of Gilbert, Stevin appeals to the ability of magnets to maintain their orientation in space to explain this phenomenon, eliminating the need for a separate third motion (Stevin, 1961: pp. 127–31).

7.

Thomas Digges (ca. 1546–1595) was the son of English mathematician Leonard Digges (Johnson and Starkey, 1934; McIntyre, 2000). After his father's early death, Thomas Digges studied mathematics with John Dee. He published several works on applied mathematics, including surveying, ballistics, and astronomy, some of which had been begun by his father. His observations of the 1572 nova appeared in *The Wings or the Ladder of Mathematics* (*Alae sev scalae mathematicae*, 1573), a work that Tycho Brahe cited with some approval, and like Brahe he concluded that the nova was supralunar. He speculated that its dimming was caused by the annual motion of the Earth and rejected the possibility that the new star was physically dimming or shrinking on the grounds that such a change would be contrary to physics. He also expressed the hope that parallax observations would decide between the Copernican and Ptolemaic systems (Digges, 1573: fols. 2A 2 v-2A 3 v). Digges' enthusiasm for Copernicus manifested itself in the *Wings* but he did not yet commit himself fully.

In 1576, when Digges published a new edition of his father's popular almanac *A prognostication everlasting of righte good effecte,* he appended two texts. One, in which he listed the problems then current in navigation, has no direct bearing on astronomy. The other text, a free translation of sections of Book I of *On the Revolutions,* is entitled *A Perfit description of the Caelestiall Orbes.* Digges translated those chapters explaining the arrangement of planets in a heliocentric system and refuting philosophical arguments against terrestrial motion. However, he believed that the surest proof of heliocentrism lay in Copernicus' mathematical demonstrations of planetary motion, which could only be appreciated by mathematically skilled readers. Because only Copernicus produced "true and certaine" effects, his system was based on true causes, unlike the faulty geocentric system (Digges, 1576: fol. M 1 v).

Digges also stated as a certainty what Copernicus had diffidently mentioned as a possibility, namely the infinite extension of the sphere of fixed stars (Digges, 1576: fol. N 4 r; cf. Copernicus, 1543: fol. 6 r). The removal of the constraints of 24-hour rotation and outer invisible orbs which had explained precession and trepidation allowed the sphere of stars to become fixed and of indefinite size. Despite his shift to a heliocentric, unbounded universe, Digges retained elements of the traditional Ptolemaic-Aristotelian cosmology. A diagram shows the Earth and other planets carried by orbs in a heterogeneous cosmos, with a central Sun and an unchanging realm of nonplanetary stars. The Earth alone remained the "globe of mortalitye" opposed to the eternal supralunar region, which was the dwelling place of angels and "the elect." (Digges, 1576: fol. 43 r).

8.

Diego de Zúñiga (also known as Diego Rodríguez Arévalo) (1536–ca. 1600) was a Spanish Augustinian who held the chair of Holy Scripture at the University of OSuna during the 1570s and published widely in an attempt to attract patronage from the papacy and the King of Spain. On leaving OSuna he made a clear endorsement of physical Copernicanism in a 1584 book, and an equally clear dismissal of the doctrine in a later one (Brotóns, 1995).

De Zúñiga's *Commentaries on Job* appeared at Toledo in 1584, and was reprinted in Rome in 1591. As evidence in favor of Copernicus' view he cites improved accuracy in specifying planetary positions, and especially Copernicus' explanation of the precession of the equinoxes and the length of the year. He also claims that the Sun is known to be forty thousand stades closer to the Earth than it was in ancient times. Zúñiga goes on to reconcile Copernicanism with the understanding of the Bible, using the common sixteenth-century strategy of Accomodationism. The Bible, he suggests, is written in the common speech, and is not, therefore, a reliable indication of the structure of the world revealed by learned investigation. Indeed the motion of the Earth could be taken as evidence of "the marvellous power and wisdom of God" who is able to maintain in motion such a heavy body (Zúñiga, 1584: pp. 205–7; cf. Brotóns, 1995: pp. 67–9).

Although Zúñiga's favorable tone is clear, it is perhaps significant that none of the evidence he brings forward supports either axial rotation or orbital motion unequivocally. The improved accuracy in specifying planetary positions could be achieved using Copernicus' mathematical models referred to a central, stationary Earth, as Reinhold and his successors at Wittenberg actually did. Neither the precession of the equinoxes nor the definition of the length of the year require the adoption of heliocentrism. The motions of the equinoxes can be referred to the sphere of fixed stars, or ancillary spheres enclosing it, although, as we have seen, some Copernicans, such as Rheticus, considered this objectionable. Similarly, the length of the year corresponds to a motion that can be attributed to a moving Sun leaving the Earth stationary. In a later work on motion, based on Aristotelian physics but employing the concept of impetus, Zúñiga argues persuasively against physical Copernicanism.

In *Philosophy, Part One* (*Philosophia prima pars*), the first of a projected trilogy which appeared at Toledo in 1596, Zúñiga rejects both the axial rotation and the annual motion of the Earth. Against axial rotation he uses standard Aristotelian arguments that falling objects, or objects thrown straight upward, would show perceptible effects if the Earth were in motion. Additionally, things in their natural element, such as birds and clouds, would be left behind by a rotating Earth. Also, the Earth is mutable and might be damaged by a daily rotation. The heavens are immutable and would suffer no similar damage. It is therefore preferable to locate the daily rotation in a movement of the heavens. The annual motion of the Earth is rejected on the curious grounds that the Sun, rather than the Earth, is responsible for the seasons. The only seeming vestige of Zúñiga's earlier position is his admission that the size of the universe may be so great that it is impossible to say whether the Earth or the Sun is at the center. (Brotóns, 1995: pp. 72–4).

Brotóns (1995) suggests that Zúñiga may have modified his position on Copernicanism after early indications that the doctrines of heliostatism and the motion of the Earth might prove theologically problematic. However, it is also notable that Zúñiga never considers any detailed arguments from the nature of planetary motion in Ptolemaic astronomy, such as the ability of Copernicus to explain the size, location and duration of retrogradations, or other advantages such as the abolition of the equant. By confining himself almost exclusively to the relations between the Earth, Sun and fixed stars, Zúñiga's claim that the universe is too large to be able to fix a center also allows him to attribute any motion he desires to either a moving Sun (in his 1584 book) or a stationary Earth (in his 1596 book). There is no indication that he saw Copernican astronomy as a pretext to criticize or abandon Aristotelian physical principles. Quite the contrary, he seems to continue to endorse one of the major current versions of Aristotle's account of motion, impetus theory. The 1596 rejection of Copernicanism may therefore also be seen as the natural consequence of Zúñiga thinking through the cases of motion treated by Copernicus in terms of Zúñiga's own preferred account, and finding in favor of a geocentric cosmos for physical rather than astronomical reasons.

9.

Giordano Bruno (1548–1600), born Filippo Bruno of the Italian town of Nola, took the name Giordano when he became a Dominican (Yates, 1970). He left the monastery after questioning the Trinity, and became an itinerant scholar who frequently moved to avoid trouble with authorities. From 1583 to 1585 he lived in England where he defended Copernicus against Oxford scholars in a debate he later made famous in *The Ash Wednesday Supper* (La *cena de le ceneri,* 1584/1977). He wrote a number of other works touching on cosmology; in this paper we shall focus on his remarks on Copernicus in *On Immensity and Innumerable Things, or On the Universe and the Worlds* (*De immenso et innumerabilibus, seu de universo et mundis,* 1591/1879–84). The recurring theme of the infinite universe that first surfaced in the Oxford debate suggests he was familiar with Digges' work. In 1593 he was taken to the Inquisition at Rome, where he was eventually executed for heresy.

Bruno modified his admiration of Copernicus with the charge that the latter neglected physics and gave a purely mathematical account of heliocentrism. (Bruno, 1879–84: i.i p. 395; 1977: p. 395). He felt that an exact mathematical description of celestial motion was impossible because material bodies moved irregularly, not in perfect circles (Bruno, 1977: pp. 221–24). As an atomist, Bruno rejected peripatetic physics according to which simple bodies moved with simple motions; therefore, he denied that planets were carried by orbs in combinations of circular motions. Instead he divided matter into hot and cold bodies. Cold bodies such as the Earth necessarily circled hot bodies such as the Sun in order to receive their warmth and generate life. In contrast to Digges, Bruno advocated a homogeneous cosmology, with each star another Sun accompanied by its own Earths (Granada, 1997). Our Sun no longer occupied a special place, and other cold bodies were not necessarily better than our Earth (Bruno, 1977: pp. 90–91).

Bruno's emphasis on physics may correlate with limited mathematical knowledge; he employed little mathematics in his writings and sometimes miSunderstood technical aspects of Copernican astronomy. At the time of the *Ash Wednesday Supper*, Bruno interpreted the cosmological diagram in *On the Revolutions* as depicting both Earth and Moon on the circumference of a single epicycle circling an empty central point, which he insisted was necessary to explain the annual variation in distance of the Earth from the Sun (Bruno, 1977: pp. 190–93). In *On Immensity and Innumerable Things* he adopted the conventional view that placed the Moon on an epicycle centered on the Earth. But he criticized Copernicus for placing Mercury and Venus closer to the Sun than the Earth-Moon system was. Instead, Bruno located Mercury on the same circle as the Earth but diametrically opposed to it, with Venus circling it as another Moon in a Pythagorean "counter-Earth" system. He then lapsed to the system of the *Supper* with the addition of Venus and Mercury on the circumference of their own shared epicycle (Bruno, 1879–84: i.i pp. 395–98). The slightly less radical *Immensity* version of Copernicanism loses the ability to explain the bounded elongation of Mercury (which should always be in conjunction with the Sun) and the distance-velocity relationship of the planets. In its most extreme version, it cannot explain the differing bounded elongations and periods of Mercury and Venus or even the monthly revolution of the Moon. Frances Yates concluded that for Bruno, the Copernicus diagram was less a depiction of physical reality than a Hermetic "hieroglyph" (Yates, 1964: p. 241). Nonetheless he insisted on the importance of a non-Aristotelian physics, with which heliocentrism seems to have been most compatible.

10.

William Gilbert (1540–1603), an English physician who began practicing medicine in London in the mid-1570s, was a prominent figure in English magnetic studies (Pumfrey, 2000). His only two published works, *On the Magnet* (*De magnete*, 1600) and *On the World* (*De mundo*, published posthumously in 1651), place magnetism at the center of an alternate physics which is friendly to heliocentrism, although Gilbert never committed to Copernicanism in print. *On the Magnet*, reported to have been finished in the 1580s, focused on studies of the magnet, with cosmology limited to Book VI; *On the World*, probably begun around the time *On the Magnet* was finished and still incomplete at Gilbert's death, attempted to give an account of the world based on magnetic forces (Gatti, 1999: pp. 86–87). According to Gilbert, the Earth itself is a giant spherical magnet rotating daily on its axis by virtue of its magnetic nature. Like Maestlin and Stevin, he argued that the rotation of a small body was more reasonable than the daily revolution of the entire heavens, and he attempted to quantify its speed (Gilbert, 1958/1600: pp. 318–27). Unlike Maestlin, but like Bruno, he rejected solid celestial orbs as fictions (Gilbert, 1651: pp. 147–58). The fixed stars lay at various distances from the Earth, some indeed at distances beyond comprehension; because an infinite body cannot move, he reasoned, both daily motion and precession must be attributed to the Earth instead of to an indefinitely large starry realm or a pretended ninth sphere.

In both books Gilbert openly endorsed terrestrial rotation but put off the question of the reality of heliocentrism. While his private opinion cannot be known with certainty, some Gilbert scholars regard him as a probable Copernican (Freudenthal, 1983; Gatti, 1999: pp. 96–98). Gilbert's magnetic philosophy eradicated the terrestrial-celestial distinction because all bodies were composed of the same fundamental matter, the magnetic element. The Sun imparted motion to the five planets; there is no reason why it should not cause the Earth to move in the same way. His diagram of the world, reproduced in *On the World*, shows the other planets on circles centered on the Sun. No circle is present to indicate whether Earth goes around Sun or *vice versa*, leaving open the option of a heliocentric or geoheliocentric system (Gilbert, 1651: p. 202). However, the stars freely scattered through space are centered on the Sun, and in a Tychonic interpretation of the diagram the outer planets would intrude on the region of stars (Freudenthal, 1983: p. 32).

11.

The appearance of Kepler's *Mystery of the Cosmos* in 1596 marks a change in Copernican doctrine which is completed in the *New Astronomy* of 1609. Although Kepler's ideas are slow to spread, the version of Copernicanism that he develops in these two works ultimately provides the foundation for the modern form of the doctrine. These books also mark the transition to a defense of Copernicanism based on factors extrinsic to astronomy. Although Kepler succeeds in providing a predictive astronomy more accurate than any predecessor, he links the subject in new ways to both physics and theology (Barker and Goldstein, 2001; Barker, 2002).

The *Mystery of the Cosmos* is the first book-length defense of Copernicanism to appear since *On the Revolutions* itself (Kepler 1981/1596). In the first chapter Kepler rehearses the main arguments offered by previous Copernicans. The new system can offer a causal explanation for the number, extent and duration of retrogradations, as Kepler explains in detail with the aid of diagrams. These are unusual in showing the Ptolemaic epicycles of the planets drawn to scale. Ptolemy never explains why the epicycle for Mars is vastly larger than the epicycle for Jupiter, which in turn is larger than that for Saturn. Copernicus offers a simple explanation for this scaling effect (in modern terms we would say that each epicycle corresponds to the Earth's orbit viewed from the planet's mean distance). The same considerations also explain the Ptolemaic linkage between the planetary models and the position and motion of the mean Sun. Copernicus' system is also economical; many motions follow from the introduction of a very few orbs. And, as a student of Maestlin, Kepler is aware that the motion of the comet of 1577 fitted into the Copernican orb for Venus (and, by implication, could not be fitted into a Ptolemaic or Aristotelian pattern of orbs). A final reason for preferring Copernicus' system is that it is more plausible to attribute the daily motion to a small body like the Earth than a large one like the sphere of fixed stars (Kepler, 1981: pp. 75–85). However, where most previous Copernicans continued to accept the Aristotelian doctrine that planets are passively carried through space by orbs in which they are embedded, Kepler rejects solid heavens for a continuous fluid substance in which the spheres and orbs are no more than geometrical boundaries.

Kepler's main, and original, argument for Copernicanism occupies the balance of the book. It is, simply put, that God employed the Platonic regular solids exactly once each in establishing the plan of the world. As there are five solids they may be used to define six circumscribed and inscribed orbs. This immediately explains another fact Ptolemy is silent about: why there are six planets. The most important demonstration, however, is that the geometrical construction provided by the solids and their inscribed spheres defines the distances between the planets and the Sun as they appear in Copernicus' system, and not as they appear in Ptolemy's. Kepler's derivation is motivated in part by the belief, common among Lutheran followers of Melanchthon, that the world has been providentially ordered by God, and that the truths of mathematics, and hence of astronomy, are certain because they are inscribed on the soul when it is created. Thus God has provided the means to uncover and to understand his providential design, and this is just what

Kepler believes he has done. The mystery of the universe is a sacred mystery. The obvious secret is that the Divine plan uses the Platonic solids as scaffolding. Behind that a further secret is implied – God is a Copernican. Kepler has therefore provided the strongest possible argument for the compatibility of the Copernican system with the Christian faith (Barker, 2000a; Barker and Goldstein, 2001).

The argument of the *Mysterium* leaves certain questions open. It defines the distances but does not explain the motions of the planets, and lacking the solid spheres that carried planets in earlier cosmological schemes, it demands an explanation for the causes of planetary motion. Kepler resolves all these questions in the *New Astronomy* (1992/1609). In short order he shows that a heliocentric "floating equant" model is more accurate in predicting planetary longtitudes than either Ptolemy's geocentric models, Copernicus' original models based on the mean Sun, or the hybrid geo-heliocentric model recently introduced by Tycho Brahe. Kepler also shows that the planes of planetary motions so defined coincide in the real Sun, and not the mean Sun which formed the center of Copernicus' system. Despite its relative success, Kepler rejects the "floating equant" model in turn as inaccurate and unphysical. He introduces a force, centered on the Sun but attenuating with distance, that sweeps the planets around as the Sun rotates. Based on this force he derives what we would now call the second law of planetary motion (the area law) first in the case of eccentric circular motions, and finally in the case of an ellipse. The ellipse is introduced specifically to accommodate data on both the longitude of a planet and its distance from the Sun. The motions on the ellipse is therefore a real physical motion in three-dimensional space and may properly be called an "orbit" – a term Kepler introduces (Stevenson, 1994; Barker and Goldstein, 2001).

Although planets might be imagined to have three-dimensional paths in earlier cosmic schemes, the astronomical theories associated with them, including that of Copernicus, are concerned only to calculate the angular position of planets with respect to some appropriate line of reference. Although it is possible to calculate distances in Ptolemaic astronomy (Van Helden, 1985), these items had never been combined to define a continuous track through space specifying both the planet's direction and distance at any moment. The modern concept of planetary motion is just that planets move freely through space, and that their orbits may be calculated to determine their positions. This formulation of Copernican doctrine begins with Kepler, and ultimately becomes canonical (through the work of Newton) despite being resisted by other Copernicans like Galileo.

To put the comparison in its starkest form: Copernicus provided a heliocentric system in which the planets were embedded in spheres or orbs which transported them through space. Copernicus' planets performed epicyclic motions but only their angular velocities, not their distances from the Sun and from each other, played a role in calculating their positions as viewed from the Earth. The reference point from which these motions began was not the position of the Sun itself but an empty point, the mean Sun. Kepler not only replaced circles by ellipses but more importantly replaced calculations that specified only the direction to a planet with calculations that defined an orbit, a path through space with both a definite direction and a definite distance. He described a heliocentric system in which planetary orbits intersected in the physical Sun, and planets moved freely through a fluid heaven in response to a force coming from the Sun. It remained for Newton to clarify the nature of this force in precise detail. Kepler, then, tied Copernicanism to physical questions such as the precise role of the Sun in astronomical calculations and the forces that create or sustain planetary motion.

12.

Concurrent with Kepler's intellectual revision of Copernicus came Galileo's introduction of significant new evidence in the cosmological debate of the early seventeenth century. Galileo attended the University of Pisa but never finished a degree, choosing to abandon the medical training his father wanted for him in favor of continuing his mathematical studies privately. In May of 1609 he was a professor of mathematics at the University of Padua in the Venetian Republic when he learned of the recent invention of the telescope by the Dutch lensmaker Hans Lipperhey. He began constructing his own telescopes and soon learned how to make superior instruments with greater magnifying power than available imports. Initially Galileo, like most of his contemporaries, only thought of using the device for terrestrial observations. One telescope he gave to the Republic in exchange for a salary increase and a lifetime position at the university, after demonstrating its utility for naval and military reconnaissance. By November he had finished manufacturing an even better instrument, with which he began to make observations of the heavens (Van Helden, in Galileo, 1989).

Galileo's first publication on his telescopic observations – indeed, the very first work published on the telescope as an astronomical instrument – was the *Sidereal Messenger* (1610), in which he describes his observations of the Moon, the fixed stars, and the moons of Jupiter, and draws strongly pro-Copernican conclusions. The Moon was the first subject of Galileo's study. Irregularities in the terminator led Galileo to conclude that the surface of the Moon itself was uneven. He interpreted the shifting patterns of light and shadow as mountains receiving illumination while valleys remained in shadow. Contrary to the Aristotelian doctrine of a perfect and immutable celestial realm, the Moon was a flawed and Earthlike body. Galileo emphasized this point by comparing its bright and dark regions to land and sea. He also noted that the dark part of the cresent Moon in reality shone with a faint light visible to the naked eye, a phenomenon he identified as Earthshine. Although it seems dark to its inhabitants, the Earth resembles a planet in its brightness and ability to illuminate other bodies (Galilei, 1989/1610: pp. 39–57; Cohen, 1985: pp. 58–64).

Galileo made two important discoveries when he turned his telescope to the fixed stars. Whereas the planets could be resolved into small disks, the stars remained points, meaning that they were very distant. Although not conclusive evidence, this supported heliocentrism, which required an enormous universe to explain the lack of observed stellar parallax. He also discovered many new stars invisible to the naked eye. Human senses were therefore not infallible and the ancients did not know everything about the heavens. The last discovery to make its way into the *Sidereal Messenger* was that Jupiter has four moons of its own, named by Galileo the "Medicean stars" after his patron Cosimo de Medici. The discovery removed one objection against Copernicanism, namely that it required multiple centers of motion. The moons circling Jupiter demonstrated that our Moon could also move around a moving Earth (Galilei, 1989: pp. 56–85; Cohen, 1985: pp. 64–65, 71–72).

Galileo continued to investigate the heavens with his telescope. In 1612 he entered into a debate with Christoph Scheiner over the interpretation of what appeared to be dark spots on the Sun; Galileo's side of the debate was published by the Lincean Academy as *History and Demonstrations Concerning Sunspots and Their Phenomena* (*Istoria e dimonstrazioni intorno alle macchie solari,* 1613). Scheiner identified them as small planets passing in front of the Sun, while Galileo maintained that they were imperfections on the surface of the Sun itself. Because the spots appeared, changed shape and size, moved with respect to each other, and then disappeared, the Sun must be subject to generation and decay. In the letters Galileo also described the phases of Venus. Through a telescope it became apparent that Venus goes through a complete set of phases similar to the Moon, appearing nearly full when smallest and crescent when largest. This is impossible in the Ptolemaic system, for Venus would always lie below the Sun and would never become full; therefore, Venus must circle the Sun (Galilei, 1957/1613; Cohen, 1985: pp. 72–74).

In these two publications, Galileo represented his discoveries as overthrowing Aristotle and upholding Copernicus. In reality, none of them contain irrefutable evidence for heliocentrism. His work on the Moon, the fixed stars, and Sunspots attacked the terrestrial-celestial distinction and lessened the difficulties of making the imperfect Earth a planet. The Jovian moons provided irrefutable evidence for more than one center of motion, and the phases of Venus removed one objection against Copernicus (whose system required such phases), but both findings equally supported the Tychonic system. Nevertheless, Galileo's telescopic work was significant because it increased the plausibility of the Copernican system while weakening the Ptolemaic one.

13.

Our survey of physical Copernicans before 1610 has revealed a great distance between early and modern forms of Copernicanism. For the first Copernicans, astronomy defined planetary motions in terms of angles viewed from a moving Earth, not continuous paths through space. Many continued to accept the mechanism that had explained planetary motion in pre-Copernican astronomy, namely non-overlapping orbs or spheres carrying planets around a fixed center. Copernicus himself continued to think in these terms. Spheres appear in the work of Rheticus, Gemma Frisius, Stevin, Digges, and Maestlin, while Zúñiga remains silent on the question of spheres in his writings on Copernicus. Only Rothmann, Bruno, Gilbert, Kepler and Galileo clearly reject the existence of solid spheres. None of the five worked in the period immediately after the publication of *On the Revolutions*, and the last two are key figures in the transition to modern Copernicanism. Most important, the abandonment of solid spheres was a necessary condition for the emergence of modern Copernicanism in Kepler's thought, since it allowed him to envision planets freely moving through space in noncircular orbits. The modern form of Copernicanism therefore presupposes non-Copernican answers to the questions of the substance of the heavens and the physical causes of planetary motion. However, rather than criticizing Copernicus for getting the answers to these question wrong, it would be more accurate to say that he simply did not raise them.

It is also worth noting, in passing, that reconciling religion and science was not a major problem for Copernicans before 1610. Although Wittenberg astronomers like Peucer had developed a canonical list of scriptural objections to Copernicanism by the early 1550s, both the Protestant Rothmann and the Catholic Zúñiga felt free to defend the compatibility of novel cosmological doctrines with the Bible, and both used the same strategy, Accomodationism. Kepler also defended Copernicanism against Biblical criticisms.

He also deployed Accomodationist arguments in the introduction to the *New Astronomy*, and the whole of the *Mystery of the Cosmos* may be read as a religious defense of Copernicanism, although it must be admitted that this particular attempt to reconcile heliocentrism and Christianity made few converts. The entire situation began to change with the controversies that embroiled Galileo leading up to the condemnation of 1616, although Zúñiga's 1596 rejection of Copernicanism may be an early indication that the climate within parts of the Catholic church was already changing. However, the hardening of Church opinion against Copernicanism must be understood primarily as a rejection of Copernicanism as it existed in the period we have considered, and not its later form. And it is apparent that none of the arguments offered before Kepler and Galileo were strong enough to convince many people or to shelter the new doctrine from theological sniping.

The first followers of Copernicus fall into two main groups. The larger group consists of mathematicians: Rheticus, Gemma Frisius, Rothmann, Maestlin, Stevin, and Digges. These authors articulated a coherent set of arguments for adopting heliocentrism based on the technical parts of *On the Revolutions*, though not every author presents all the arguments. We suggest two pro-Copernican arguments as especially significant in understanding the mathematical approach. First, Copernicus creates a relationship between the velocity of a planet and its distance from the center of the world: outer planets are necessarily slower. Second, he can explain, for the first time, the position, magnitude, and duration of retrogradations, which Ptolemy predicted by arbitrarily tying the motion of a planet's epicycle to the motion of the Sun. Thus Copernicus provides a potential methodological advantage, because he can explain these matters in a way that conforms to Aristotelian standards for causal explanations where Ptolemy cannot. A much smaller group consists of physicists: Zúñiga, Bruno, and Gilbert. Bruno, as we have seen, failed to understand even fundamental consequences of astronomical models and contradicted the first mathematical argument. Gilbert showed little interest in the mathematical arguments. The indecisiveness of these arguments is underlined by the observation that not all early Copernicans retained their favorable opinion of his cosmology. Rothmann and Zúñiga first accepted and then rejected heliocentrism. Rheticus' silence about the issue in later life may indicate a retraction of his initial enthusiasm. Even Gilbert's status as a heliocentrist is marginal.

The situation changes with the entry of Kepler and Galileo into the cosmological debate. In contrast to earlier Copernicans, they use mathematics primarily to make physical claims. (In the case of Galileo, this approach becomes clearer in his later publications, which fall outside the scope of this paper.) Where Aristotelians had emphasized qualitative, causal demonstration, Kepler and Galileo turned to mathematical demonstration as the preferred methodology. After 1610 the two groups of early Copernicans, the mathematicians and the physicists, are replaced by the new "mathematical physicists" advocating a form of Copernicanism much more familiar to modern readers.

The work of Copernicus and his immediate followers is conceptually consistent with Ptolemaic astronomy, and employs an equally consistent methodology and epistemology; however, the work of Kepler and Galileo, to which this led, breaks with Ptolemy and introduces new epistemological themes. Hence the work of Copernicus set in motion a train of events that led to a decisive epistemological shift, but did not itself represent such a shift. There is no abrupt adoption of Copernicus in the period immediately following 1543. The real revolution is the replacement of the methods and goals of Ptolemaic astronomy and Aristotelian physics with Copernicanism in its modern form, which incorporates the conceptual structure of Kepler and the astronomical evidence of Galileo. Such a version of Copernicanism is not available before 1610. Understanding the revolution requires careful analysis of the process up to that point. Our study shows that the change in astronomy after the publication of *On the Revolutions* constitutes a "revolution" as understood by philosophy of science. However, it was not a single great event. The Copernican Revolution was a protracted process consisting of many small steps, and the changes within Copernicanism were almost as great as those separating heliocentrism from geocentrism.

Bibliography

Barker, Peter. 2000a. "The role of religion in the Lutheran response to Copernicus". In: Margaret J. Osler (Ed.), *Rethinking the Scientific Revolution*, pp. 59–88. Cambridge University Press, Cambridge.

Barker, Peter. 2000b. "Maestlin, Michael (1550–1631)". In: Wilbur Applebaum (Ed.) *Encyclopedia of the Scientific Revolution from Copernicus to Newton*, pp. 378–379. Garland, New York.

Barker, Peter. 2000c. "Rothmann, Christoph (fl. 1555–1597)". In: Wilbur Applebaum (Ed.) *Encyclopedia of the Scientific Revolution from Copernicus to Newton*, pp. 579–580. Garland, New York.

Barker, Peter. 2002. "Constructing Copernicus". In: Peter Barker (Ed.) *New Foundations in the History of Astronomy. Perspectives on Science.* Cambridge, Mass., 10 (2/2002), pp. 208–27.

Barker, Peter. "How Rothmann Changed His Mind". In: Peter Barker, A. Bowen et al. (Eds.) *Astronomy and Astrology from the Babylonians to Kepler. Centaurus.* Copenhagen 46 (1/2004), pp. 41–57.

Barker, Peter, and Bernard R. Goldstein. 1998. "Realism and Instrumentalism in Sixteenth Century Astronomy: A Reappraisal". *Perspectives on Science,* Cambridge, Mass., 6 (3/1998), pp. 232–258.

Barker, Peter, and Bernard R. Goldstein. 2001. "Theological Foundations of Kepler's Astronomy". In: John Hedley Brooke, Margaret J. Osler, and Jitse van der Meer (Eds.) *Science in Theistic Contexts: Cognitive Dimensions. Osiris,* 2nd series. Ithaca 16, pp. 88–113.

Barker, Peter, and Bernard R. Goldstein. 2003. "Patronage and the Production of *De revolutionibus*". *Journal for the History of Astronomy,* Cambridge, 34 (4/2003), pp. 345–368.

Brotóns, Victor Navarro. 1995. "The Reception of Copernicus in Sixteenth-Century Spain: The Case of Diego de Zúñiga". *Isis,* Chicago 86 (1/1995), pp. 52–78.

Bruno, Giordano. 1879–84. *De immenso et innumerabilibus, seu de universo et mundis.* In *Opera latine conscripta.* F. Fiorentino, V. Imbriani, et al. (Eds.). i.1 p. 191–1.2 p. 318. Dom. Morano, Naples/Florence. [Facsimile reprint: Friedrich Fromman Verlag, 1961–62.]

Bruno, Giordano. 1977. *The Ash Wednesday Supper.* Edward A. Gosselin and Lawrence S. Lerner (Ed. and Transl.). Archon Books, Hamden. English translation of *La cena de le ceneri,* J. Charlewood, London, 1584.

Burmeister, Karl Heinz. 1967–68. *Georg Joachim Rhetikus: Eine Bio-Bibliographie.* 3 Vols. Pressler-Verlag, Wiesbaden.

Cohen, I. Bernard. 1985. *The Birth of a New Physics.* Revised ed. W. W. Norton & Co., London.

Copernicus, Nicolaus. 1543. *De revolvtionibvs orbium coelestium, Libri VI.* Ioh. Petreium, Nuremberg.

Digges, Thomas. 1573. *Alae sev scalae mathematicae …* . Thomas Marsh, London.

Digges, Thomas. 1576. *A perfit description of the Caelestiall Orbes according to the most auncient doctrien of the pythagoreans &c.* In: Leonard Digges, *A prognostication euerlastinge of right good effect …* . Thomas Marsh, London.

Freudenthal, Gad. 1983. "Theory of Matter and Cosmology in William Gilbert's *De magnete*". *Isis,* Philadelphia, 74 (1/1983), pp. 22–37.

Galilei, Galileo. 1957. "Letters on Sunspots". In: *Discoveries and Opinions of Galileo.* Stillman Drake (Transl.), pp. 87–144. Doubleday, New York. English translation of *Istoria e dimonstrazioni intorno alle macchie solari e loro accidenti …,* Giacomo Mascardi, Rome, 1613.

Galilei, Galileo. 1989. *Sidereus Nuncius or The Sidereal Messenger.* Albert Van Helden (Transl.). University of Chicago, Chicago. English translation of *Siderevs Nvncivs …* . Thomas Baglionus, Venice, 1610.

Gatti, Hilary. 1999. *Giordano Bruno and Renaissance Science*, Cornell University Press, Ithaca.

Gemma Frisius. 1555. "Epistola ad I. Stadius". In: I. Stadius, *Ephemerides novae et exactae ab a. 1554 ad a. 1570*, fols. a 1 r – a 2 v. A. Birkmann, Cologne.

Gilbert, William. *De Magnete.* P. Fleury Mottelay (Transl.). Dover, New York, 1958. English translation of *De magnete, magneticisqve corporibvs, et de magno magnete tellure; physiologia noua …* . Petrvs Short, London, 1600.

Gilbert, William. 1651. *De Mundo nostro Sublunari Philosophia Nova. Opus posthumum …* . Ludovicum Elzevirium, Amsterdam.

Goldstein, Bernard R. 1987. "Remarks on Gemma Frisius' *De radio astronomico et geometrico*". In: J. L. Berggren and B. R. Goldstein (Eds.), *From Ancient Omens to Statistical Mechanics: Essays in the Exact Sciences Presented to Asger Aaboe*, pp. 167–79. University Library, Copenhagen.

Goldstein, Bernard R. 2002. "Copernicus and the Origins of His Heliocentric System". *Journal for the History of Astronomy*, Cambridge, 33 (3/2002), pp. 219–235.

Goldstein, Bernard R., and Peter Barker. 1995. "The Role of Rothmann in the dissolution of the celestial spheres". *British Journal for the History of Science*, Cambridge, 28 (4/1995), pp. 385–403.

Grafton, Anthony. 1973. "Michael Maestlin's Account of Copernican Planetary Theory". *Proceedings of the American Philosophical Society*, Philadelphia, 117 (6/1973), pp. 523–50.

Granada, Miguel A. 1997. "Thomas Digges, Giordano Bruno e il copernicanesimo in Inghilterra". In: Michele Ciliberto and Nicholas Mann (Eds.), *Giordano Bruno, 1583–1585: The English Experience*, pp. 125–55. S. Olschki, Florence.

Johnson, Francis R., and Sanford V. Larkey. 1934. "Thomas Digges, The Copernican System, and the Idea of the Infinity of the Universe in 1576". *Huntington Library Bulletin*, Cambridge, 5 (April/1934), pp. 69–117.

Kepler, Ioannes. 1981. *Mysterium Cosmographicum: The Secret of the Universe.* A. M. Duncan (Transl.). Norwalk, CT, Abaris Books. English translation of *Prodromus dissertationem cosmographicarum, continens mysterium cosmographicum.* Gruppenbach, Tübingen, 1596.

Kepler, Ioannes. 1992. *New Astronomy.* William H. Donahue (Transl.). Cambridge University Press, Cambridge. English translation of *Astronomia nova AITIOLOGETOS, sev physica coelestis.* Voeglinus, Heidelberg, 1609.

Kish, George. 1967. *Medicina, Mensura, Mathematica: The Life and Works of Gemma Frisius, 1508–1555.* Associates of the James Ford Bell Collection, Minneapolis.

Lammens, Cindy. 2002. *Sic patet iter ad astra: A critical examination of Gemma Frisius' annotations in Copernicus' De Revolutionibus and his qualified appraisal of Copernican theory.* 3 vols. Ph.D. dissertation, Universiteit Gent.

Maestlin, Michael. 1578. *Observatio et demonstratio cometae aetherei, qui in anno 1577 et 1578 constitutus in sphaera Veneris, apparuit.* Gruppenbach, Tübingen.

Maestlin, Michael. 1581. *Consideratio et observatio cometae aetherei astronomica, qui anno MDLXXX … apparuit.* Jakob Muller, Heidelberg.

McIntyre, Gary. 2000. "Digges, Thomas (ca. 1546–1595)". In: Wilbur Applebaum (Ed.) *Encyclopedia of the Scientific Revolution from Copernicus to Newton,* pp. 191–192, Garland, New York.

Methuen, Charlotte. 1996. "Maestlin's Teaching of Copernicus: The Evidence of His University Textbook and Disputations". *Isis,* Chicago, 87 (2/1996), pp. 230–47.

Peucer, Caspar. 1569. *Elementa doctrinae de circvlis coelestibvs, et primo motu, recognita et correcta.* Iohannes Crato, Wittenberg.

Pumfrey, Stephen. 2000. "Gilbert, William (1544–1603)". In: Wilbur Applebaum (Ed.) *Encyclopedia of the Scientific Revolution from Copernicus to Newton,* pp. 266–68. Garland, New York.

Reinhold, Erasmus. 1542. *Theoricae novae planetarum Georgii Purbacchii, Germani, ab Erasmo Reinholdo Salveldensi … .* Lufft, Wittenberg.

Reinhold, Erasmus. 1551. *Prutenicae tabulae coelestium motuum.* Morhard, Tübingen.

Rheticus, Georg Joachim. 1971. *Narratio prima.* In: Edward Rosen (Transl.), *Three Copernican Treatises,* pp. 107–196. 3rd. ed. Octagon, New York. English translation of *Ad clarissimvm virvm D. Ioannem Shonervm, de libris revolvtionum … narratio prima,* Franciscus Rhodus, Danzig, 1540.

Rosen, Edward. 1974. "Mästlin, Michael". In: Charles Coulston Gillispie (Ed.), *Dictionary of Scientific Biography,* vol. 9, pp. 167–170. Charles Scribner's Sons, New York.

Rothmann, Christopher. 2003. *Christoph Rothmanns Handbuch der Astronomie von 1589: Kommentierte Edition der Handschrift Cristoph Rothmanns "Observationum stellarum fixarum liber primus", Kassel 1589.* Miguel A. Granada, Jürgen Hamel, Ludolf von Mackensen (Eds.). Harri Deutsch, Frankfurt am Main.

Russell, John L.1972. "The Copernican System in Great Britain". In: Jerzy Dobrzycki (Ed.), *The Reception of Copernicus' Heliocentry Theory,* pp. 189–239. D. Reidel, Dordrecht.

Stephenson, Bruce. 1994. *Kepler's Physical Astronomy.* Princeton University Press, Princeton.

Stevin, Simon. 1605–8. *Wisconstighe gedachtenissen. Hypomnemata mathematica …* Willebrodus Snellius (Tr.). Johannes Patius, Leiden.

Simon Stevin. 1961. A. Pannekoek (Ed.), C. Dikshoorn (Tr.). *Principle Works of Simon Stevin.* Vol 3: *Astronomy.* C. V. Swets & Zeitlinger, Amsterdam.

Tredwell, Katherine A. 2004. "Michael Maestlin and the Fate of the *Narratio prima*". *Journal for the History of Astronomy,* Cambridge, 35, forthcoming.

Van Helden, Albert. 1985. *Measuring the Universe: Cosmic Dimensions from Aristarchus to Halley*. Chicago University Press, Chicago.

Vermij, Rienk. 2002. *The Calvinist Copernicans*. Royal Netherlands Academy of Arts and Sciences, Amsterdam.

Westman, Robert S. 1972. "The Comet and the Cosmos: Kepler, Mästlin and the Copernican Hypothesis". In: Jerzy Dobrzycki (Ed.), *The Reception of Copernicus' Heliocentric Theory*, pp. 7–30. D. Reidel, Dordrecht.

Westman, Robert S. 1975. "The Melanchthon Circle, Rheticus, and the Wittenberg Interpretation of the Copernican Theory". *Isis*, Washington, D.C., 66 (232/1975): pp. 164–193.

Westman, Robert S. 1980. "The Astronomer's Role in the Sixteenth Century: A Preliminary Survey." *History of Science*, Bucks, England, 18 (2/1980), pp. 105–147.

Yates, Frances A. *Giordano Bruno and the Hermetic Tradition*. University of Chicago Press, Chicago 1964.

Yates, Francis A. 1970. "Bruno, Giordano". In: Charles Coulston Gillispie (Ed.), *Dictionary of Scientific Biography*, vol. 2, pp. 539–544. Charles Scribner's Sons, New York.

Zúñiga, Diego de. 1584. *Didaci a Stunica … in Iob commentaria, quibus triplex eius editio vulgata Latina, Hebrææa, & Grææca septuaginta interpretum, necnon & Chaldææa explicantur*. I. Rodericus, Toledo.

Zúñiga, Diego de. 1596. *Philosophia prima pars, qua perfecte et eleganter quatuor scientiae metaphysica, dialectica, rhetorica et physica declarentur*. I. Rodericus, Toledo.