Chapter 6
"Qualis alio modo reperiri non potest." A Few Words on Copernican Necessity

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I will examine what counts as necessary in the Copernican world, primarily as presented in Book I of *De revolutionibus orbium coelestium* (1543). In doing so, I will consider how Copernicus offers his system as an *idea mundi*, such that the intellectual vision of the astronomer converges with the divine vision of necessity. My reading here owes a particular debt to Georg Joachim Rheticus (1514–1574) and Johannes Kepler (1571–1630) and to the astronomical frontispieces of Oronce Fine (1494–1555). I also ask what necessities Copernican astronomy imposes on material bodies. I argue that Copernicus presents matter as perfect—perfectly incarnating geometry—at the cosmographical-astronomical scale. Material contingency, for him, arises only at smaller scales. My analysis of these issues extends to numerous points within Copernicus's context and within the sixteenth-century reception of his work.

6.1 Introduction

The title of this article comes from Book I of *De revolutionibus orbium coelestium* (1543). In Chap. 10, Nicolaus Copernicus (1473–1543) gives a summary of the new celestial order: the Earth and other planets circle the Sun, which stands immobile at the center of the world. "In this arrangement," writes Copernicus, "we discover a marvelous symmetry of the universe, and an established harmonious linkage between the motion of the spheres and their size, such as can be found in no other way (*qualis alio modo reperiri non potest*)."[1] This *such as can be found in no other*

[1] Copernicus (1978, 22). Copernicus (1543, ff. 9v–10r).

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P. D. Omodeo, R. Garau (eds.), *Contingency and Natural Order in Early Modern Science*, Boston Studies in the Philosophy and History of Science 332,
https://doi.org/10.1007/978-3-319-67378-3_6

way is perhaps as close as Copernicus comes to a global claim for necessity—a claim for why his ordering of the planets is necessary over and above the others. It might be useful to summarize what he means here. In Ptolemaic mathematical astronomy, the planets were modeled individually. If an astronomer changed the distance of a particular planet from the Earth, he would be under no obligation to adjust any of the other planetary distances.[2] In this sense, Mercury could be made the outermost planet, as long as it was also granted extraordinary fleetness. The traditional ordering of the planets, says Copernicus, was assumed according to optical principles: the farther a body from an observer, the slower it seems to move. But if we allow for a moving Earth, he continues, we can establish the planetary order *with certainty*. He means that, presupposing a moving Earth, the astronomer can calculate planetary distances using the Earth-Sun radius as a common measure[3] (the word "*symmetria*" refers to this network of proportions[4]). In turn, it can be shown with certainty that the slower a planet, the greater its distance from the center. The agreement of distance and period is that "linkage of harmony" (*nexus harmoniae*) to which Copernicus refers. Why he felt symmetry and harmony to be a principle advantage of his system has remained open for debate.[5] For the moment, we should recall that Book I also presents another necessity: celestial orbs must rotate uniformly. Copernicus is here railing against the equant, the Ptolemaic device for modeling the variable speed of a planet as it turns around its center. Any non uniformity, says Copernicus, would be caused by inconstancy (*inconstantia*) exerted from within or without the moving body. He flatly concludes that it would be inappropriate (*indignum*) to impute such inconstancy to the celestial bodies, "objects constituted in the best order."[6]

The theme of this volume offers an opportunity to consider what is *necessary* in Copernican philosophy, by which I mean that amalgam of astronomical and physical speculation laid out in Book I of *De revolutionibus orbium coelestium*. In turn, we can ask what counts as contingency. This line of questioning can give additional perspective on one of the critical issues in Book I, namely, the relationship between mathematical reasoning and physical reasoning. I will argue that Copernicus makes the sweeping eye of the mathematician—of the astronomer and cosmographer—converge with the divine eye of necessity. Copernican appeals to symmetry and

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2 Neugebauer (1975, 146).

3 Copernicus used parallax for distance calculations. See Swerdlow and Neugebauer (1984, 232–271). For a discussion of the Copernican distances in light of Ptolemy's *Planetary Hypotheses* (of which Copernicus, like all sixteenth-century European astronomers, was unaware), see Ibid., 472–479.

4 According to Giora Hon and Bernard Goldstein, Copernicus used *symmetria* in the Vitruvian sense, as the fitting proportion between parts and between parts and whole. Hon and Goldstein (2008, 157–163). Mehl prefers to read *symmetria* as commensurability between celestial motions. Mehl (2016).

5 Robert Westman has made certainty of planetary distances the underlying motivation for Copernicus. For Westman, Copernicus wished to establish such certainty in order to shore up astrology against attacks from Pico della Mirandola. Westman (2011).

6 Copernicus (1978, 11). Copernicus (1543, f. 3r).

uniformity are best understood in this sense, as features of the *idea mundi*. If there is any truly necessary point of physical necessity, it is that matter must coalesce into perfect spheres at the astronomical and cosmographical scale. The operative word here is "scale." Nature follows its perfect order at large scales, where geometrical form dominates. As one zooms into a landscape, contingencies appear. This is not a question of coarse-graining. Copernicus seems committed to transferring the ancient perfection of celestial matter to the elements, so long as we consider them from the divine perspective. Finally, I will briefly touch upon animism or vitalism in *De revolutionibus*, since early Copernicans attempted to build a Copernican physics wherein life—the vitality of celestial bodies—was a necessary principle. Throughout the study, I will pay special attention to Georg Joachim Rheticus (1514–1574) and Johannes Kepler (1571–1630) for help with interpretation.

6.2 Symmetry, Uniformity, and the *idea mundi*

The question of certainty and uncertainty is in the marrow of the Copernican corpus, as well as in the historiography of Copernican astronomy and its reception. Most readers, past and present, take him to believe in the truth of his system. But belief and truth are a matter of degree. And Copernicus was aware that he could not prove the reality of terrestrial movement but only show it plausible and preferable.[7] This begs the question of what he wished to accomplish with his physical arguments in Book I. Thomas Kuhn thought that they were a half-hearted attempt to clear space for his astronomy, to show that terrestrial immobility was *not* necessary and mobility therefore possible.[8] More recent appraisals have reconsidered the text both for its internal logic and within its wider context of natural philosophy and mixed mathematics.[9]

The longest shadow cast over the landscape of Copernican historiography must be Pierre Duhem's, for it was Duhem who first systematically explored disciplinary tensions in which the Copernican invention appeared. In his *Sauver les apparances* (1908), he presents a history of astronomy from the Greeks to Galileo driven by tension between two camps we can refer to as instrumentalist and realist.[10] The first camp was constituted by thinkers who saw astronomy as a geometrical practice, employing a minimum number of physical principles. Its goal was to "save the

[7] As Noel Swerdlow puts it, "He was in the situation—not infrequent in the sciences, in scholarship, in law—of being certain that he was right, but lacking conclusive proof." Swerdlow and Neugebauer (1984, 21).

[8] Ibid., 144–45.

[9] For a review of Copernicus's physical ideas and their Scholastic precedents, see Omodeo (2014, 197–233). For the humanist side of Copernicus's physical ideas, see Knox (2005). For an overview of Copernicus's sources, see Goddu (2010). For a comprehensive analysis of the internal logic of Book I, see Szczeciniarz (1998).

[10] Duhem (2004 [1908]).

appearances," that is, to reproduce the heavenly motions. This position was set out by the Greeks. The second camp insisted that astronomical motions must correspond to *real* bodies. Members of this latter camp wanted astronomy tied to physics. Sometimes they set astronomy backward, ossifying theory. Sometimes, in thinkers like Kepler and Galileo Galilei (1564–1642), they advanced science through their stubbornness, delusion, brilliance, and good luck. Duhem's own instrumentalism is well known, so it comes as no surprise that he believes the Greeks had it right (so far as he interprets them), and he traces their scientific attitude—their preference for mathematics and physical parsimony—as it is passed from Posidonius to Simplicius, by way of Geminus, Ptolemy, and Proclus.[11] In Duhem's narrative, the correct balance between mathematical invention and physical constraint was then upset by Arabic philosophers, literalists who read Aristotle to the letter. Duhem's account of Arabic astronomy is the weakest point of the volume and a regrettable piece of Orientalism. In any case, he has medieval Catholic schoolmen in Paris, Aquinas, and Bonaventure, setting things aright. Latin Averroists continued to exert influence into the sixteenth century, however. From their base at the University of Padua, they tried to construct a properly Aristotelian, homocentric astronomy. Duhem places Copernicus as a disciple of these Averroists, demanding that astronomy satisfy homocentricism and uniform motion.[12] Duhem has Copernicus first experimenting with the Earth's movement as a fictitious hypothesis and then adopting it as the truth. This is how Copernicus himself describes his path. By Duhem's logic, Copernicus only errs when fiction becomes reality.

Thanks to recent scholarly work, we know that thoroughgoing instrumentalists or fictionalists (to use what is no doubt a problematic and anachronistic set of terms) were rare among sixteenth-century astronomers.[13] Most astronomers took the orbs to be real in some sense, as did Copernicus. But while there is little doubt that Copernicus thought celestial orbs were real, it is difficult to say *what* exactly they were for him. Noel Swerdlow has made the strongest case for solid spheres. He shows that early on, Copernicus was aware of the geo-heliocentric option (usually referred to as the Tychonic system, after its subsequent champion, Tycho Brahe). In this system, the Earth remains immobile and central. The planets circle the Sun, which in turn circles the Earth. Swedlow argues that Copernicus rejected the Tychonic system because Mars, near its perigee, clips the Sun's orb, an intersection impossible to reproduce with solid spheres. So, Swedlow concludes, Copernicus adopted the heliocentric system because it *was* amenable to Peurbach-type orbs.[14]

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[11] Ibid. 89–90.

[12] "Copernic conçoit le problème astronomique comme le conçoivent les physiciens italiens dont il a été l'auditeur ou le condisciple; ce problème consiste à sauver les apparences au moyen d'hypothèses conformes aux principes de la Physique. […]." Ibid., 84.

[13] See Barker and Goldstein (1998); Shank (2002); Barker (2011).

[14] Swerdlow relies on his discovery of a page of notes, handwritten by Copernicus, in a manuscript held by the Library of Uppsala. As mentioned, these notes show Copernicus working through calculations for what would become the *Commentariolus*. Swerdlow (1973).

In other words, the orbs reflected a physical necessity that set bounds on mathematical possibility.[15] Other prominent historians have made equally strong arguments that solid orbs were not a Copernican necessity.[16]

In a note to the second edition (1621) of the *Mysterium cosmographicum*, Johannes Kepler says that Copernicus never believed in adamantine spheres (*corpulentia adamantina*). Not even Ptolemy, he continues, had entertained such a monstrous concept.[17] This 1621 note is confusing on the historical front, because it contradicts earlier pronouncements. Twenty years earlier in his *Apologia pro Tychone contra Ursum* (c. 1600), Kepler had stated that Copernicus had never envisioned a mixed model like Brahe's: the possibility of the Sun going around the Earth, and the planets around the Sun, would have been unfathomable to Copernicus, who “believed in the reality of the orbs.”[18] Likewise, in the *Astronomia nova* (1609), Kepler had written that Copernicus had required uniform motion because of solid spheres (*orbis solidus*).[19] Had Kepler changed his mind by 1621? Maybe. But what he implies in the 1621 note is that he had *always* taken Copernicus to posit the spheres as a *spatium geometricum orbium.*[20] The spheres should be just thick enough for all the necessary geometrical demonstrations to fit.[21] It would be worth citing

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[15] In several articles, Edward Rosen reacted violently against Swerdlow's argument. For Rosen's Copernicus, planetary orbs are hollow, mutually penetrable, and intersecting. Rosen (1976, 302).

[16] Nicholas Jardine asks how Copernicus's earth, surrounded by air, could attach to a solid orb. Jardine prefers to see the orbs as impenetrable and non solid. Jardine (1982, 177). Edward Grant has written that there was no explicit rule during the Middle Ages and the Renaissance as to the exact qualities of the celestial orbs. Their solidity or fluidity was never a “genuine issue,” although they were certainly corporeal. Copernicus, according to Grant, fits very well within the medieval mold, insofar as he does not present his “explicit opinions about the rigidity or fluidity of the orbs” Grant (1987, 172–173). Grant's observation seems backed up by the fact that Copernicus never employs the word “solidus” to describe *sphaerae* or *orbes*. The celestial spheres were often described as crystalline in medieval philosophy, but according to Goldstein and Barker, “crystalline” was meant primarily to convey that the spheres had crystal's transparency. Goldstein and Barker (1995, 392).

[17] KGW viii, 84, n.1.

[18] Jardine (1984, 70).

[19] KGW iii, 73: “Ergo idem orbis solidus (quos opinatur COPERNICVS) in quo haeret PIaneta, tardus est, cum Planeta orbe vectus incedit ex D in E [apogee to a point in the nearest quadrant]; velox, cum it ex E in F [to perigee]. Totus ergo orbis solidus jam velox jam tardus est. Quod COPERNICVS ut absurdum rejicit.” Swerdlow marshals both this passage and the passage from Kepler's *Apologia* for support, in Swerdlow (1976, 131–132).

[20] KGW viii, 84 (n. 1): “*Nostris Philosophis assentitur COPERNICVS*. Intellige de spatio Orbium Geometrico: de materia enim, hoc est, de corpulentia adamantina ne PTOLEMAEVS quidem adeo crasse philosophatur.”

[21] “So let us come now to our principal subject. It is known that the planetary paths are eccentric. And hence the received judgment among natural philosophers (*physicis*), which establishes that the orbs be as thick as is required for the demonstrated variety of movements. And so far as this, Copernicus agrees with our philosophers.” KGW i, 47: “Igitur vt ad principale propositum veniamus: notum est, vias planetarum esse eccentricas: et proinde recepta physicis sententia, quòd obtineant orbes tantam crassitiem, quanta ad demonstrandas motuum varietates requiritur. Et hactenus quidem nostris Philosophis assentitur COPERNICVS.”

another quote from the *Mysterium*, this time from the text of the *Mysterium*'s first edition (1596), where Kepler says that Copernican orbs cannot be contiguous, because then they would have to be monstrous: "[…] it is seen that in Copernicus no orb is tangent to another but there are immense intervals assuredly filled with a celestial air, which attach to neither of the two neighboring systems."[22]

There is often an ambiguity about orbs and spheres in the Renaissance. Are they mathematical or physical, fluid or hard? Kepler preserves "*orbis*" to describe the paths taken by planets as they are driven by the Sun. He never cleanses the term entirely of its solid-sphere connotations. One such connotation is thickness. Kepler's model in the *Mysterium* works, in part, by ascribing a purely geometrical thickness to the planetary spheres: "I give to the orbs themselves as much thickness as is required by the ascent and descent of the planet."[23] This thickness, the difference between apogee and perigee is simply a mathematical object, a certain quantity. Although Kepler rejects solid spheres, he underlines their architectural sense: the planetary orbs with their relative distances set by the Platonic solids constitute the *idea mundi* fixed in the divine mind.[24] Kepler's orbs are also, it goes without saying, as stable as the most perfect façade: the relationship between Sun and planet is one-way, and the planets do not influence one another, so there is no perturbation in the modern sense. Unlike Newtonian orbits, they do not degrade. Their architectural nature should remind us of Kepler's hefty drawing of the polyhedra in the *Mysterium*, where they form what looks like a marble sculture too heavy to ever move from the garden.

For Kepler, the most compelling feature of Copernican astronomy was not uniformity. Not at all, in fact, since he would embrace non uniform motion as proof that the sun acted as a motor on the planets.[25] Instead, Kepler was obsessed with Copernican *symmetria*. The central claim of the *Mysterium* is that Copernican planetary distances manifest the divine order of a mathematical creator. Given that the planetary distances could be known with certainty (as proportions of the Earth-Sun radius), Kepler wanted to understand why *these* distances were expressed instead of others. What made them necessary? His solution was that they expressed proportions inherent in the Platonic solids, polyhedra that held a place of privilege in the *Timaeus* (which Copernicus cites at least once[26]) and in Euclid's *Elements*. Kepler believed the *Timaeus* to be a work of the highest philosophical and religious significance, and his own take on a mathematical God and the *idea mundi* is drawn

[22] Here is the quote in its fuller context. KGW i, 48: "Quae haec Naturae luxuries? Quam inepta? Quam inutilis? Quam minime ipsi vsitata? Atque ex hoc videre est, in COPERNICO nullum orbem ab alio tangi, sed ingentia relinqui systematum interualla vtique plena coelesti aura, sed ad neutrum tamen propinquorum systematum pertinentia."

[23] KGW i, 48: "Orbibus ipsis tantam relinquo crassitiem, quantam requirit ascensus descensusque planetae […]"

[24] For the *idea mundi* in the *Mysterium cosmographicum*, see KGW i, 23–26. Kepler uses the variant spelling "*idaea*."

[25] From the *Mysterium* onward, he believed that planets slowed as they grew further from the Sun because the Sun exerted a force that weakened with distance. He turned this intuition into a principle of his celestial physics.

[26] Knox (2002, 403–405).

from it. The polyhedral hypothesis can be read as a response to the dedication and first book of *De revolutionibus*, and especially to Rheticus's *Narratio prima* (Danzig: 1540), which was appended to both editions of the *Mysterium*. The *Narratio*, appearing 3 years before *De revolutionibus,* was the first published explanation of Copernican astronomy. Because Rheticus composed it while staying in Frauenburg as Copernicus's guest, we can assume that his presentation is more or less in keeping with his master's opinion. In the treatise, Rheticus presents "the admirable symmetry and interconnection of the motions and spheres preserved by the aforementioned hypotheses," using the same language later found in *De revolutionibus*, namely, "*admiranda symmetria*" and "*nexus.*" He notes that these features are really best understood not via language but by an immediate comprehension of the mind: "not so much by words as by the perfect and absolute ideas, if I may use the term, of these most delightful objects."[27] Such appeals to the divine *idea mundi*, acute in the work of Kepler and as a visual motif in seventeenth-century astronomical books,[28] are not exotic in the first half of the sixteenth century. We might consider the dedication to Jacques Lefèvre d'Étaples's (c. 1450–1536) 1517 introduction to astronomy, which Duhem notes and approves of for its view of astronomical hypotheses as fictions.[29] Lefèvre d'Étaples says that mathematical astronomy is a results-oriented affair of imagination. Yet imagination is not equivalent to unreality or fantasy, as Duhem takes it, but rather operates as the link between sense and reason, as it generally did in the Renaissance. Lefèvre d'Étaples emphasizes similarity and imitation: astronomical practice is an imitation of divine creation, and so its products are copies or likenesses of real things. The language, especially the use "*effictus*" and "*simulacrum,*" is highly redolent of Cicero's partial translation of the *Timaeus*, the *Liber de universitate ex Timaeo Platonis*[30]:

> For this part of astronomy is almost entirely imaginative and productive. And not otherwise than the wisest and best artisan, through the workings of his divine mind, created the real heavens and real motions, our mind, emulating the father (whenever our fault of ignorance is wiped away slightly) brings forth copied heavens (*effictos ceolos*) and copied motions (*effictos motus*) and within them certain simulacra of the true motions, as it seizes the truth within traces of the workings of the divine mind. The mind of the astronomer, then, when it carefully depicts (*effingit*) the heavens and motions of the heavens, resembles the artist of [all] things creating the heavens and motions of the heavens. […] The mind then resembles the eye in which the ethereal orbs and motions of the orbs are represented without confusion.[31]

[27] Copernicus and Rheticus (1959, 145). KGW i, 104 (this is the Latin reprinting of the *Narratio* appended to the first edition of the *Mysterium cosmographicum*).

[28] See Söderlund (2010, 177–187).

[29] Lefèvre d'Étaples (1517). Duhem (2004, 66).

[30] See sections 6–8 of Cicero (1977). *De universitate* was first printed in 1485 in a volume including *De fato* and *Topica*, with commentary by Giorgio Valla. *De universitate* was reprinted a handful of times in the sixteenth century.

[31] "Nam haec astrologiae pars: tota ferme imaginaria effectrixque est. Et haud secus quod rerum sapientissimus optimusque opifex veros coelos & veros motus divinae mentis opificio producit: mens nostra sui semper aemula parentis (cum ignorantiae labes plusculum detergitur) effictos coelos effictosque motus intra se profert verorumque motuum simulachra quaedam in quibus ut in vestigiis divinae mentis opificii depraehendit veritatem. Est igitur astronomi mens cum coelos

Both Copernicus and Rheticus suggest the possibility for convergence between the *mens astronomi* and the divine intellect or the divine perspective. In the Copernican scheme, there are two accurate points of view, where an observation coincides with real motions through space. The first is from the center of the *mundus*. The second is from outside the system, where the entire world is taken in at once. In this, the Copernican system is not unique from geocentric astronomy. The difference comes into play when we, the observers, are set moving. Copernicus frames earthly movement as a virtue rather than a liability. To be locked into place, even at the center, makes knowledge of planetary distance impossible—the conclusions achieved by Copernicus in Book V, relying on measured parallax, would be impossible. Unfortunately, while motion brings understanding, it also distorts our sight. Therefore, if we want an ideal picture of the universe—one that provides an accurate vision of distance and motion—it must be the intellectual vision that an astronomer reaches only after observation, calculation, and reflection. It is the diagrammatic view, and it is the vision closest to God's own appreciation of his handiwork, as Copernicus suggests in his dedication to the Pope (now remembered for his commissions of Michelangelo).[32]

There is a long-running question of whether Platonic philosophy played a decisive role in Copernicus's work.[33] The link between astronomy and the divine is found in both Aristotelian[34] and Platonic philosophy and is expressed clearly in the *Almagest*, in a famous passage where the symmetry (συμμετρία) of the heavens is associated with God, a passage that Copernicus clearly echoes.[35] I would simply like to point out that in Copernicus, the mathematical understanding of the astronomer takes precedence over physical questions, specifically those of efficient and material cause. We could say that the *imago mundi* leads to the *idea mundi*, such that the diagrammatic puts the astronomer in direct contact with the necessity of the ideal. For an illustration (literally) of this point, we might consider Oronce Fine's (1494–1555) frontispiece for a 1515 edition of Georg von Peuerbach's *Theoricarum novarum textus* (Fig. 6.1).[36] Ptolemy is staring up through an astrolabe.

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coelorumque motus gnaviter effingit: similis rerum opifici coelos coelorumque motus creanti. […] Iterum mens similis est oculo in quo aetherei orbes orbiumque motus sine confusione repraesentantur." Lefèvre d'Étaples (1517, f. a1v). Duhem provides a problematic translation of the above text. Besides his anachronistic reading of "imaginary," the main problem is that he translates "*effictus*" as "*fictif*." This is a stretch, as "*effictus*" usually refers to a copy taken from life, as in a portrait.

[32] For more on the humanist themes at play in Copernicus's preface dedicated to the Pope, see Westman (2011, 133–40).

[33] On Copernicus's reading of Ficino, see Knox (2002) and Goddu (2010, 225–229). Anna de Pace argues for the decisive influence of Platonic philosophy on Copernicus in De Pace (2009). I was unable to consult her volume during the writing of this article. Also see Vesel (2014, 306–338).

[34] "[…] dans la perspective de la théologie astrale qu'Aristote développe dans le *De philosophia* et qui demeurera, encore qu'épurée, le fondement de toute sa spéculation théologique, l'astronomie nous fournit une expérience immédiate du divin; elle représente, si l'on peut ainsi parler, l'aspect expérimental de la théologie" (Aubenque 1962, 329).

[35] Ptolemy (1984, 37).

[36] Peuerbach (1515, f. 1v).

Fig. 6.1 Georg von Peuerbach, *Theoricarum novarum textus Georgii Purbachii cum… expositione Domini Francisci Capuani* (Paris: Michael Lesclencher, 1515), f. 1v. Courtesy of the Bayerische Staatsbibliothek
* B&W frontispiece in copy held by Bayerische StaatsBibliothek
http://reader.digitale-sammlungen.de/de/fs1/object/display/bsb10196228_00010.html

Astrologia, at far left, instructs an unnamed astronomer-astrologer. Countryside, rolling hills, and villages fold out behind them. The huge armillary sphere—Earth, zodiac, and great circles—is planted on a solid pedestal at the astronomers' feet.[37] In the image frame is a rather cryptic motto of uncertain origin: *Altior incubuit animus sub imagine mundi*. We might take this to mean that the superior mind reposes under the image of the world, awaiting inspiration in dreams.[38] This seems to be the message of the 1527 frontispiece by Oronce Fine from his edition of Sacrobosco's *Sphaera* (Fig. 6.2).[39] Here a winged Mercury points to an astronomer laying in a field, in a situation of peaceful sleep or meditation. It is hard to tell whether his eyes are open or closed. His understanding of the cosmographical scheme seems to arise from celestial inspiration. Under his hand, on the ground, is what seems to be a manual with some sort of geometrical diagram. Most of the image is occupied by a massive astronomical-cosmographical diagram, showing the principle spheres. This is the *imago mundi* referred to in the inscription.

So what about uniformity? As Copernicus says to the Pope, his first motivation was annoyance in finding a lack of certainty about the celestial motions among philosophers, given that the *machina mundi* was created for our sake by the best and most regular (*regularissimo*) creator.[40] The firmest reason for uniformity provided by Copernicus is that celestial bodies can brook no inconsistency, because they are established *in optima ordinatione*. This is divine necessity, the necessity of the *idea mundi*. Copernicus is saying little more.[41]

6.3 Sphericity as Physical Necessity

So far, we have discussed necessity from a design point of view. Yet there is a lot of physics in Book I of *De revolutionibus*, which begins like other works of astronomy that had come before: by establishing the sphericity of the "*mundus*." In Aristotelian or Ptolemaic astronomy, a spherical shell of stars makes sense. Every day, the stars

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[37] This earth-planted sphere can also be seen in the frontispiece of Regiomontanus's *Epytoma in Almagestum Ptolomei*.

[38] I have followed Isabelle Pantin's translation. She cites the *Aeneid*, VII, 88, where *incubuit* refers to the priest reposing and awaiting prophetic dreams. Pantin (2009, 69).

[39] Sacrobosco (1527).

[40] Copernicus (1543, f. 3r).

[41] Likewise, in a wide swath of Scholastic and Renaissance thought, the necessity expressed by heavenly bodies is generally linked with their formality, regularity, predictability, and uniformity. In Book X of the *Republic*, Plato has all the celestial orbs turning around the spindle of necessity (ἀνάγκη). Plato (1935, 616c, 500–501). In Aristotle, the heavens are incorruptible, unwavering, and eternal. Averroes grants them necessity because they are "eternal and never fail to produce their effect." Belo (2007, 170). As Pietro Daniel Omodeo notes in his chapter, Aquinas ascribes necessity to the celestial bodies because they are dominated by form, in contrast with sublunar matter, whose inherent mutability is the root of contingency. Such examples could be multiplied *ad nauseum*.

Fig. 6.2 Sacrobosco, *Sphaera*, ed. Oronce Fine (Paris: Simon Colines, 1527). Courtesy of the Bibliothèque interuniversitaire de santé (BIU Santé), Paris

must turn in a complete revolution. This movement has profound consequences in Aristotelian physics—it is the first motion and the source of time. But once we assume the Earth to rotate diurnally, there is no benefit to having the stars stuck to an orb. The necessity of a stellar sphere seems to vanish, as it would for later "heliocentrists" like Thomas Digges (c. 1546–1595) and Giordano Bruno (1548–1600). Copernicus himself famously refuses to take a position on the infinity of the world, leaving the question to natural philosophers. But why? Isn't Copernicus suggesting a great deal of natural philosophy in Book I? Yes, but it is a natural philosophy motivated almost entirely by a consideration of the Earth. All that he will say about the wider *mundus* is that it self-coheres: "wholes strive [*appetant*] to be circumscribed by this boundary, as is apparent in drops of water and other fluid bodies when they seek to be self-contained."[42] Water is an important entity here, because Copernicus makes it into an example of how matter can collect into separate spheres or local centers. Copernicus echoes Pliny: "For we see everywhere, that drops, when they hang down, assume the form of small globes (*parvis globantur orbibus*), and when they are covered with dust, or have the down of leaves spread over them, they are observed to be completely round […]"[43] Copernicus may also have in mind Cicero in the Stoic Book II of *De natura deorum*. The separate celestial bodies are described by Cicero as perfect spheres held together by their *nisus*, a pressure or internal force. In turn, their motion is conserved because of their sphericity: "they are round, that is the shape, as I believe I remarked before, that is least capable of receiving injury."[44]

Copernicus suggests the self-cohesion of celestial bodies because he wants to talk about the self-cohesion of the Earth—he wants to underline similarities between celestial and terrestrial bodies. For Aristotle and Cicero, the sphericity of heavenly bodies is of a higher order than that of the Earth. They are more perfect, more refined. Aristotle, speaking with the terminology of craftsmen, writes that the precision (ἀκρίβεια) with which the stellar sphere is rounded (ἔντορνος) utterly surpasses anything in our environment: "with each step away from earth the matter manifestly becomes finer in the same proportion as water is finer than earth."[45] Later Aristotelians also drew attention to the unearthly smoothness and perfection of the celestial spheres, which spin at high speed without a hitch.[46] One of the really subversive elements of Copernican physics, however, is to make the Earth the standard of spherical perfection and so a standard of ontological perfection. Copernicus calls the Earth's sphericity "*absoluta*" at two points—that is, absolute or perfect. The

[42] Copernicus (1978, 8). Copernicus (1543, f. 1r).

[43] Pliny (1855, II 65). Simplicius (2004, 66–68). Knox also notes the reference to Pliny and echo of Cicero. Knox (2005, 189–191).

[44] "In aethere autem astra volvuntur, quae se et nisu suo conglobata continent et forma ipsa figuraque sua momenta sustentant; sunt enim rutunda, quibus formis, ut ante dixisse videor, minime noceri potest." Cicero (1933, II 46).

[45] *De caelo*, II 4. For Cicero, presenting the Stoic cosmos, celestial bodies are composed of a flame that is close to the living and divine fire (*ignem*) or *pneuma*.

[46] For example, Oresme (1968, 440 114c).

absoluteness or perfection of the globe is not immediately understood because of mountains and valleys, but these negligibly change its "universal rotundity" ("*universam rotunditatem*").[47] This geometrical perfection means, of course, that we should not deny movement to the Earth. Here it is important to note that Copernicus does not claim sphericity to cause movement. But given that spherical things turn circularly, that celestial things are spherical, and that the Earth is spherical, it follows that terrestrial movement is a possibility. Or, to put it differently, terrestrial immobility is not a necessity.

But for Copernicus's argument to work, for the Earth to be truly celestial, it is necessary that it be an absolute sphere. And this in the first half of the sixteenth century was not a foregone conclusion. Ptolemy, in I 2 of his Geography, says that the "continuous surface of land and water is (as regards its broad features) spherical and concentric with the celestial sphere."[48] Ptolemy had established this to be so in his *Almagest*, although without enlarging upon a rather important detail: that the elements of earth and water share the same surface. If earth and water were somehow displaced, if their spheres did not match up, then one of the spheres would be off-kilter from the world's center. While Ptolemy's argument makes intuitive sense for us, a shared earth-water surface does not flow naturally from Aristotle, nor would it be tenable for future writers. According to a theory widely accepted from the medieval period until the late Renaissance, the center of the earth's sphere was offset from the water's. The idea is a rather neat way to harmonize Aristotle and Moses: after casting the elements in the Aristotelian order, God drew the northern hemisphere out of the vast seas, leaving the southern hemisphere submerged. He thereby separated the waters, as in *Genesis*, allowing room for plants and animals to flourish. Without God's continued decree, the dry part of the Earth would plop back under. Hence, earth and water shared neither the same center nor the same surface. This scheme, first expounded by Jean Buridan (1300–1358), was championed by important forces in the fifteenth- and sixteenth-century natural philosophy. Among them were Pierre d'Ailly (1351–1420), Gregor Reisch (1467–1525), and Sebastian Münster (1488–1552), author of the encyclopedic *Cosmographiae universalis libri IV* (first edition in German, 1544). Münster's *Cosmographia* is among the most developed examples of what we might call the "nub-Earth" hypothesis. It opens with a long look at the rapport between elements, offering an interplay of geography and biblical history:

> According to the discourse of the holy texts, and the history of Moses, we see that the Earth at the beginning of its creation was completely covered and enclosed by the expanse of the waters, until they drew back from the expanding Earth, leaving a roomy space to men and terrestrial animals for their home and to the plants meant to serve as pasture and support to all that has life. […] From that day on, the sea has never had its natural position.

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[47] This was known long before Copernicus. Theon of Smyrna writes about it in his compendium of mathematical knowledge for reading Plato. If we scaled down the earth to the size of a foot in diameter, says Theon, the highest mountains would be smaller than one fortieth the diameter of a millet seed.

[48] Ptolemy (2000, 60).

> Being drawn to the opposite of this terrestrial mass, it thus doubled its depth as it uncovered the Earth. This depth is called Ocean, the Holy Writ calls it "*tehom*", that is, the great abyss where an infinity of waters are assembled.[49]

Copernicus devotes Chap. 3 of *De revolutionibus*—"*Quomodo terra cum aqua unum globum perficiat*"—to the water-earth question. His conclusion, it can be said from the outset, is that earth and water share the same center and the same surface. He explicitly refutes the "Peripatetic" argument of ten times more water than earth. He emphasizes that water, being "fluid by nature, manifestly always seeks the same lower levels as earth and pushes up from the shore no higher than its rise permits."[50] He also cites a number of contemporary discoveries, those by Spain and Portugal, and especially the discovery of America, which he attributes to Amerigo Vespucci. America, Copernicus suggests, is probably on the opposite side of the Earth from India. In short, our globe is covered by islands and continents, with no overwhelming ocean. Voyagers like Columbus and Vespucci had themselves bought into Ptolemy's vision of the earth-water rapport, as had other cosmographers and astronomers. Peter Apian and Gemma Frisius are two good examples. Their *Cosmographia*,[51] which rivaled Müster's as the most influential of the sixteenth-century cosmography, illustrates a typical Aristotelian scheme of nested spheres, typical except for the representation of the Earth at the center, where earth and water are not separate but instead combined in land, river, and sea (Fig. 6.3). Jean-Marc Besse has drawn attention to the cutting-edge aspect of this illustration, to "the representation of the earth as a unique sphere, ontologically homogenous, composed of the elements of earth and water without interruption."[52] We can also consider the Earth in Fine's 1515 engraving and again in the 1527 engraving. In both, the cosmological Earth as part of the *imago mundi* is a sphere with one continuous earth-water surface.

When we ask about physical necessity for Copernicus, it comes down to sphericity. Matter must cohere into spheres that are perfect at certain scales, those of celestial movement and planetary form. At smaller scales—that of topography, for example—matter is not expected to behave with spherical regularity.

[49] "Par le discours des sainctes lettres, et de l'histoire de Moyse, on void que la terre au commencement de sa creation estaoit toute couerte et enclose de l'estendüe des eaux, iusqu'a ce qu'elles se retirrent, partie sur la terre s'espandant, laissant neantmoins place commode aux hommes et animaux terrestres pour leur demeure, et aux plantes qui deuoyent seruir de pasture et soustien à tout ce qui a vie […] La mer donc des ce iour n'eut point sa situation naturelle, ains estant retiree en la partie opposite de ceste masse terrestre, a autaunt redoublé sa profondeur, comme elle a descouuert de la terre. Cest profondeur s'appelle Ocean, la saincte Escriture la tomme [tehom], c'est à dire, grand' abysme: à sçauoir, où il y infinie assemblee d'eaux […]" I have cited from the French translation, Münster (1575, 6).

[50] Copernicus (1978, 9). Copernicus (1543, f. 1v).

[51] The work was first published by Apian as *Cosmographicus liber* (1524). It was expanded by Frisius, who appended to the work several of his own treatises. The Apian-Frisius *Cosmographia* went through many editions and translations.

[52] "[…] au centre de la figure, la représentation (« paysagère ») de la Terre comme sphère unique, ontologiquement homogène, composée sans solution de la continuité des éléments de la terre et de l'eau." Besse (2003, 16).

Fig. 6.3 Peter Apian and Gemma Frisius, *Cosmographia*, Antwerp: Gregorius Bontius, 1550, f. 3r. Courtesy of the Max Planck Institute for the History of Science

Local variations are for all purposes contingent. Tacitly, Copernicus exports this contingency to the other planetary bodies: instead of perfect spheres made of a completely smooth material, the planets become locales for possible landscapes. There is no noticeable tension between pure and practical mathematics here.[53] At the scales that count—astronomical and cosmographical—matter really incarnates the geometrical ideal. Copernican necessity is captured by another illustration from Apian and Frisius’s *Cosmographia* (Fig. 6.4): here is the eye of the cosmographer, whose vision can overlook variations of cities, peoples, topography, and whose Earth is foremost a projection of stellar coordinates on a perfectly smooth sphere.

[53] On this distinction, between the ideal of geometrical form and the imperfections inherent in real bodies, see section (2) of Pietro Omodeo’s contribution to this volume, *Practices and Theories of Contingency in Renaissance Approaches to Nature*.

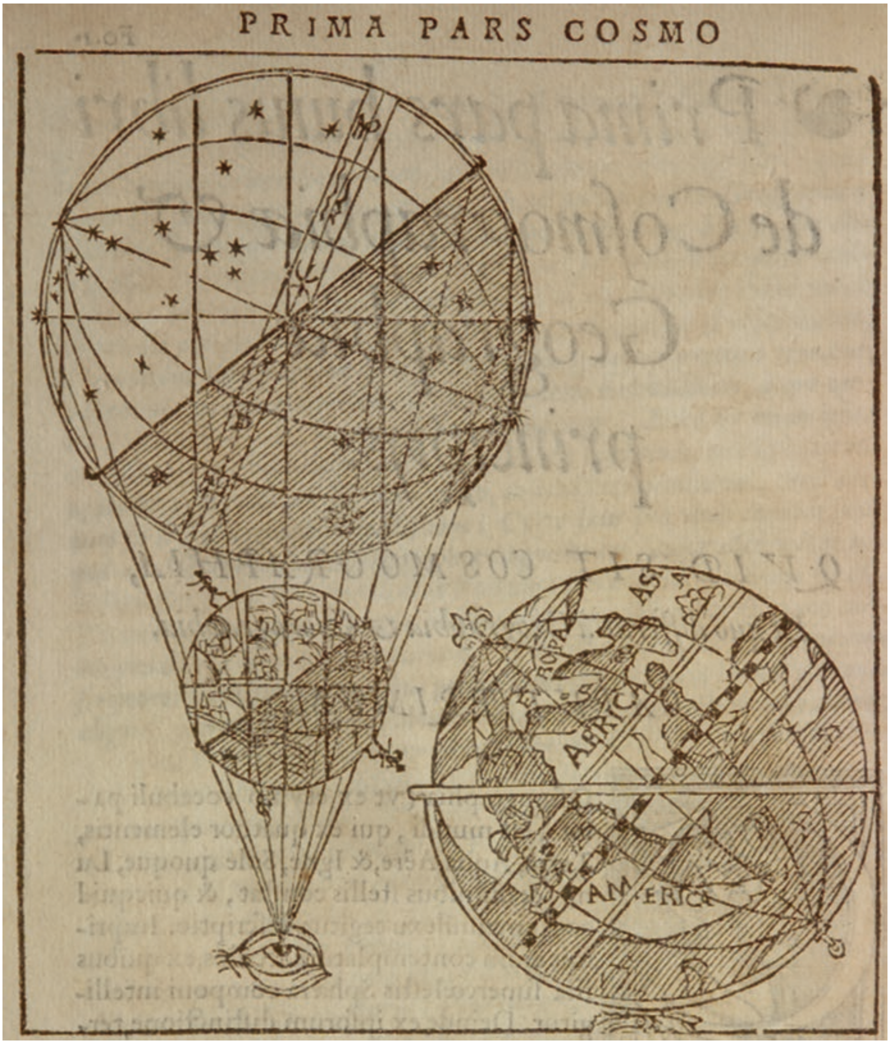

Fig. 6.4 Peter Apian and Gemma Frisius, *Cosmographia*, Antwerp: Gregorius Bontius, 1550, f. 1v. Courtesy of the Max Planck Institute for the History of Science

6.4 Toward a Natural Philosophy of the Sphere

One of the main questions for Copernicus to answer was how the Earth—or any other celestial body—held together around its unique center *and* moved. As for gravity, Copernicus writes only that matter has a natural desire (*appetentia*) implanted by God. As for the relationship between gravity and movement, Copernicus writes that since the other celestial bodies have such a natural desire, and since *they* move, there should be no problem for the Earth.[54] It might again be useful to mention the opinion of Kepler, one of Copernicus's most passionate sixteenth-century readers:

> Copernicus preferred to think that the earth and all terrestrial bodies (even those cast away from the earth) are informed by one and the same motive soul [*anima motrice informari*], which, while rotating its body the earth, also rotates those particles cast away from it. He thus held it to be this soul, spread throughout the particles, that acquires force through violent motions, while I hold that it is a corporeal faculty [*facultati corporeae*] (which we call gravity, or the magnetic faculty), that acquires the force in the same way, namely, through violent motions.[55]

How would Kepler have gotten this impression from the text of *De revolutionibus*? Copernicus reduces natural motion to the circular alone.[56] Insofar as objects participate in the whole (*universus*) of a planet, they partake in its uniform circular motion. Insofar as they are fragmented (*pars*), they have an unnatural rectilinear motion. Circular motion is permanent, whereas rectilinear motion is temporary—in this, Copernicus removes the rectilinear from natural motion. "For when rectilinear motion brings bodies to their own place, they cease to be heavy or light, and their motion ends. Hence since circular motion belongs to wholes, but parts have rectilinear motion in addition, we can say that 'circular' subsists with 'rectilinear' as 'being alive' with 'being sick.'"[57] Concerning where Copernicus might have borrowed this play of health and sickness, Reijer Hooykaas has noted that the reference to health and sickness as natural and violent motions goes back to Aristotle's *Physics*.[58] Dwilyn Knox has demonstrated as conclusively as possible that Copernicus consulted the *Suda*, a tenth-century Byzantine lexicon where many ancient and now-lost texts are compiled. When Copernicus looked up *kinesis*, he found a paraphrase of Philoponus featuring a tight ensemble of ideas about natural motion that fit closely with what we see in *De revolutionibus*: parts striving to regain the whole, wholes striving to remain together, circular motion as stasis, and recovery of health as natural motion.[59] However, that still does not answer for Kepler's "animistic" interpretation. Copernicus actually employs the Latin *animal*: "*Cum ergo motus circularis sit universorum, partium vero etiam rectus, dicere possumus manere cum recto circularem, sicut cum aegro animal*."[60] Here is the *animal* in Kepler's description of a *facultas animalis* rotating the Earth. Kepler might have seen here a validation of his own theory of an Earth soul, which he needed to explain diurnal motion, and which was crucial in his account of many terrestrial phenomena, particularly those that were astrologically induced. The cohesion of the planet, directed

[54] Copernicus (1978, 18).

[55] KGW iii, 28, 10–15. Kepler (1992, 58–59).

[56] See Chap. 8 of Book I. Copernicus (1978, 15–17).

[57] Copernicus (1978, 17). Copernicus (1543, f. 6v).

[58] Hooykaas (1987).

[59] Knox (2005, 205–208).

[60] Copernicus (1543, f. 6v).

throughout its parts to achieve movement, for Bruno and William Gilbert (1544–1603) paralleled the cohesion of animals. The Earth as animal gives Bruno an explanation for why matter should form local centers and why all matter does not simply rush together. For Bruno, water has a very important cohesive role in bodies—an echo of *De revolutionibus*, Book I.[61]

One of the first biological or quasi-biological interpretations of Copernican movement of which I am aware appears in François de Belleforest's introduction to his 1575 French translation of Münster's *Cosmographiae universalis liber*. Although de Belleforest was hostile to Copernicus, he manages a very sensitive account of a key passage in Book I of *De revolutionibus*:

> I do not want to pursue the question of the fixity and stability of the Earth, seeing that the holy writings put it outside of movement and enclosed under the concavity and admirable vault of the heavens. Nor do I want to put to the fore the fantastic and too insolent opinion of Copernicus, who, to show himself off as among the most skillful, wanted to contradict all philosophers and prove that the Earth is mobile and thus that its movements follow the cadence and admirable harmony of the parts of the world that circle and surround it, and that [the Earth] thus receives more conveniently [*plus à son aise*] the influences of celestial bodies.[62]

De Belleforest has in mind two sentences that follow one another in *De revolutionibus* I 10. The first sentence has been more or less passed over by historians, whereas the second (discussed earlier) is the most famous in all the Copernican literature:

> Thus indeed, as though seated on a royal throne, the sun governs the family of planets (*Astrorum familiam*) revolving around it. […] [1] Meanwhile the earth has intercourse with the sun, and is impregnated for its yearly parturition.
>
> [2] In this arrangement, therefore, we discover a marvelous symmetry of the universe, and an established harmonious linkage between the motion of the spheres and their size, such as can be found in no other way.[63]

Between sentences (1) and (2), historians have a tendency to see a rupture: as if (1) belonged to the old allegorical and (2) to the freshly mathematical. However, a clear arch runs from the noble "marriage" of the Sun and Earth to the order of the kingdom. The passage is reminiscent of Martianus Capella, whom Copernicus had

[61] For the important cohesive role of water, see Bruno (1830, 60–62). "Oltre, che il simile si vede ne le gocce impolverate, pendenti e consistenti sopra il piano: per che l'intima anima, che comprende et è in tutte le cose, per la prima fa questa operazione, che secondo la capacità del suggetto unisce, quanto può, le parti: e non è, per che l'acqua sia o possa essere naturalmente sopra o circa la terra, più che l'umido di nostra sustanza sia sopra o circa il nostro corpo." Ibid., 60–61.

[62] "Je ne veux aussi poursuivre ce qui est de la fermeté et stabilité de la terre, voiant que l'escriture saincte mesme nous la fait hors de mouvement, et enclose sous la concauité, et voulte admirable des cieux: et ne veux mettre en auant l'opinion fantastique, et trop gaillard de Copernique, qui pour se monstrer des plus habiles, a voulu contredire à tous philosophes, et prouuer que la terre est mobile, et par consequent elle a ses mouuemens qui vont suiuant celle cadence et harmonie admirable des parties du monde qui la ceignent et entourent, et reçoit par ce moien plus à son aise les influences des corps celestes […]" See first page of Belleforest's *preface de cest oeuvre au lecteur* in Münster (1575).

[63] Copernicus (1978, 22). Copernicus (1543, ff. 9v–10r).

cited earlier in Chap. 10. Copernicus had likely read Capella’s *De nuptiis Philologiae et Mercurii* (*On the Marriage of Philology and Mercury*), where Capella offers the hypothesis that Mercury and Venus circle the Sun. The famed Copernican appeal to harmony could be an echo of *De nuptiis*, which opens with an ode to universal unity, personified by the god Hymen: “You cause the elements to interact reciprocally, you make the world fertile; through you, Mind is breathed into bodies by a union of concord which rules over Nature, as you bring conciliation between the sexes and foster loyalty by love.”[64] De Belleforest, for his part, seems to have understood Copernicus to mean that the Earth would move so as to best receive the solar vitality. Bruno, Gilbert, and Kepler clearly build upon a similar interpretation, and all express the importance of the Earth’s motion for its overall fecundity (Kepler sexualizes the relationship even more explicitly, suggesting that the Earth receives real pleasure from the relationship of penetration and reception mediated by light.)[65] Bruno and Gilbert state the reason for a planet’s movement to be its health. The planet, in order to receive a judicious amount of sunlight on all its sides, must regulate both its revolution and rotation. Hilary Gatti has pointed out the importance of this “thermodynamic principle” for Bruno, descending from a merging of Copernican astronomy and Telesian natural philosophy. It was for Bruno, as Gatti writes, a biological explanation for the structured movement of infinite worlds.[66] When later Copernicans turned to the “how,” as in how harmony set itself in the world, they developed a natural philosophy where celestial bodies experienced the same necessities as animal bodies.

6.5 Conclusion

When we ask about necessity in the Copernican world, we must turn to a Platonic or Pythagorean framework. Necessity, so far as Copernican symmetry and uniformity, follows from the divine *idea mundi*, which in turn follows from divine attributes widely accepted in the Renaissance. Physical cause follows suite. The elements can be reduced to their one essential activity: they must coalesce into

[64] Stahl et al. (1977, 3). I have lightly altered their translation.

[65] “The Earth, then, which by some great necessity, even by a virtue innate, evident, and conspicuous, is turned circularly about the Sun, revolves; and by this motion it rejoices in the solar virtues and influences, and is strengthened by its own sure verticity, that it should not rovingly revolve over every region of the heavens. The Sun (the chief agent in nature) as he forwards the courses of the Wanderers, so does he prompt this turning about of the Earth by the diffusion of the virtues of his orbes, and of light. And if the Earth were not made to spin with a diurnal revolution, the Sun would ever hang over some determinate part with constant beams, and by long tarriance would scorch it, and pulverize it, and dissipate it, and the Earth would sustain the deepest wounds; and nothing good would issue forth; it would not vegetate, it would not allow life to animals, and mankind would perish.” Gilbert (1958, 224). Also see, Regier (2017).

[66] Gatti (1999, 121).

relatively perfect spheres. Their only “natural” motion must be that of the sphere—a circular revolution. I have stressed the relationship between the diagrammatic and the *idea mundi*: matter behaves with geometrical rigor at the scale captured by astronomical and cosmographical diagrams. Reading Book I, we might say that a certain contingency exists at the scale of landscapes—these are small irregularities from the overall sphericity of the planet. The distinction between “sublunar” and “supralunar” becomes the difference between what the eyes witness all around in the local landscape—bay, valley, mountain, and river—and the geometrical perfection witnessed in the mind’s eye of the astronomer. Later Copernicans would work through how to turn hints in Book I into a coherent natural philosophy. For reasons touched upon above, they chose to understand the celestial bodies as living and, as it were, possessed of the necessities and contingencies of the animal body.

Bibliography

Primary

Apian, Peter. 1524. *Cosmographicus liber*. Landshut: J. Weissenburger.

Apian, Peter, and Gemma Frisius. 1550. *Cosmographia*. Antwerp: G. Bontius.

Bruno, Giordano. 1830. In *De l’infinito universo e mondi*, ed. Adolfo Wagner. Leipzig: Weidmann.

Cicero. 1933. *De natura deorum*; *Academica*. Trans. H. Rackham. Harvard: Harvard University Press.

———. 1977. In *De Divinatione, De Fato, Timaeus*, ed. Otto Plasberg. Stuttgart: Teubner (This edition is available online through the Perseus Digital Library of Tufts University).

Copernicus, Nicholas. 1543. *De revolutionibus orbium coelestium*. Nuremberg: J. Petreius.

———. 1978. *Nicholas Copernicus on the Revolutions*, ed. Jerzy Dobrzycki. Trans. Edward Rosen. Warsaw: Polish Scientific Publishers.

Copernicus, Nicholas and Georg Joachim Rheticus. 1959. *Three Copernican Treatises*. Trans. Edward Rosen. Mineola, New York: Dover Publications.

Gilbert, William. 1958. *On the Magnet (De Magnete)*. Trans. Silvanus Phillips Thompson. New York: Basic Books.

Kepler, Johannes. 1937. *Gesammelte Werke* [KGW], ed. Walther von Dyck et al. Munich.

———. 1992. *New Astronomy*. Trans. William H. Donahue. Cambridge: Cambridge University Press.

Kepler, Jean. 1993. *Le secret du monde*. Trans. Alain Segonds. Paris: Gallimard.

Lefèvre d’Étaples, Jacques. 1517. *Introductorium astronomicum theorias corporum coelestium duobus libris complectens, adiecto commentario declaratum*. Paris: H. Stephanus.

Münster, Sebastian. 1575. *La cosmographie universelle de tout le monde*. Trans. François de Belleforest. Paris: M. Sonnius.

Oresme, Nicole. 1968. *Le livre du ciel et du monde*, ed. Albert D. Menut and Alexander J. Denomy. Trans. Albert D. Menut. Madison: University of Wisconsin Press.

Plato. 1935. *The Republic*. Trans. Paul Shorey. Cambridge, MA: Harvard University Press.

Pliny the Elder. 1855. *Historia naturalis*. Trans. John Bostock. London: H. Bohn.

Ptolemy. 1984. *Ptolemy’s Almagest*. Trans. G. J. Toomer. London: Duckworth.

———. 2000. *Ptolemy’s Geography: An Annotated Translation of the Theoretical Chapters*. Trans. J. Lennart Berggren and Alexander Jones. Princeton: Princeton University Press.

Sacrobosco. 1527. In *Sphaera*, ed. Oronce Fine. Paris: S. Colines.
Simplicius. 2004. *On Aristotle's On the Heavens 2.1–9*. Trans. Ian Mueller. Ithaca, NY: Cornell University Press.
von Peuerbach, Georg. 1515. *Theoricarum novarum textus Georgii Purbachii*. Paris: M. Lesclencher.

Secondary

Aubenque, Pierre. 1962. *Le Problème de l'être chez Aristote*. Paris: Presses Universitaires de France.
Barker, Peter. 2011. The Reality of Peurbach's Orbs: Cosmological Continuity in Fifteenth and Sixteenth Century Astronomy. In *Change and Continuity in Early Modern Cosmology*, ed. Patrick J. Boner, 7–32. Dordrecht: Springer.
Barker, Peter, and Bernard R. Goldstein. 1998. Realism and Instrumentalism in Sixteenth Century Astronomy: A Reappraisal. *Perspectives on Science* 6: 232–258.
Belo, Catarina. 2007. *Chance and Determinism in Avicenna and Averroes*. Leiden: Brill.
Besse, Jean-Marc. 2003. *Les grandeurs de la Terre : aspects du savoir géographique à la Renaissance*. Paris: ENS Éditions.
De Pace, Anna. 2009. *Niccolò Copernico e la fondazione del cosmo eliocentrico*. Milan: Bruno Mondadori.
Duhem, Pierre. 2004 [1908]. *Sauver les apparences*. Paris: Vrin.
Gatti, Hilary. 1999. *Giordano Bruno and Renaissance Science: Broken Lives and Organizational Power*. Ithaca: Cornell University Press.
Goddu, André. 2010. *Copernicus and the Aristotelian Tradition: Education, Reading, and Philosophy in Copernicus's Path to Heliocentrism*. Leiden: Brill.
Goldstein, Bernard R., and Peter Barker. 1995. The Role of Rothmann in the Dissolution of the Celestial Spheres. *The British Journal for the History of Science* 28: 385–403.
Grant, Edward. 1987. Celestial Orbs in the Latin Middle Ages. *Isis* 78: 153–173.
Hon, Giora, and Bernard R. Goldstein. 2008. *From Summetria to Symmetry: The Making of a Revolutionary Scientific Concept*. Dordrecht: Springer.
Hooykaas, R. 1987. The Aristotelian Background to Copernicus's Cosmology. *Journal for the History of Astronomy* 18: 111–116.
Jardine, Nicholas. 1982. The Significance of the Copernican Orbs. *Journal for the History of Astronomy* 13: 168–194.
———. 1984. *The Birth of the History and Philosophy of Science. Kepler's "A Defence of Tycho against Ursus" with Essays on Its Provenance and Significance*. Cambridge: Cambridge University Press.
Knox, Dilwyn. 2002. Ficino and Copernicus. In *Marsilio Ficino: His Theology, His Philosophy, His Legacy*, ed. Michael J.B. Allen, Valery Rees, and Martin Davies, 399–418. Leiden: Brill.
———. 2005. Copernicus's Doctrine of Gravity and the Natural Circular Motion of the Elements. *Journal of the Warburg and Courtauld Institutes* 68: 157–211.
Mehl, Édouard. 2016. Novum struam mundum': Kepler's Rebuilding of the Copernican 'symmetria mundi'. In *Unifying Heaven and Earth: Essays in the History of Early Modern Cosmology*, ed. Miguel A. Granada, Patrick J. Boner, and Dario Tessicini, 197–216. Barcelona: Universitat de Barcelona.
Neugebauer, Otto. 1975. *A History of Ancient Mathematical Astronomy*. Berlin: Springer.
Omodeo, Pietro Daniel. 2014. *Copernicus in the Cultural Debates of the Renaissance: Reception, Legacy, Transformation*. Leiden: Brill.
Pantin, Isabelle. 2009. *Altior incubuit animus sub imagine mundi*. L'inspiration du cosmographe d'après une gravure d'Oronce Finé. In *Les Méditations cosmographiques à la Renaissance*, ed. Cahiers V.L. Saulnier, vol. 26, 69–90. Paris: PUPS.

Regier, Jonathan. 2017. Ghosts in the Celestial Machine: A Reflection on Late-Renaissance Embodiment. In *Embodiment: A History*, ed. Justin E.H. Smith, 347–354. Oxford: Oxford University Press.

Rosen, Edward. 1976. *Reply to N. Swerdlow. Archives internationales d'histoire des sciences*. Vol. 26, 301–304.

Shank, Michael H. 2002. Regiomontanus on Ptolemy, Physical Orbs, and Astronomical Fictionalism: Goldsteinian Themes in the 'Defense of Theon against George of Trebizond'. *Perspectives on Science* 10: 179–207.

Söderlund, Inga Elmqvist. 2010. *Taking Possession of Astronomy: Frontispieces and Illustrated Title Pages in 17th-Century Books on Astronomy*. Stockholm: The Center for History of Science at the Royal Swedish Academy of Sciences.

Stahl, William Harris, Richard Johnson, and E.L. Burge. 1977. *Martianus Capella and the Seven Liberal Arts: The Marriage of Philology and Mercury*. New York: Columbia University Press.

Swerdlow, Noel. 1973. The Deriviation and First Draft of Copernicus's Planetary Theory: A Translation of the *Commentariolus* with Commentary. *Proceedings of the American Philosophical Society* 117: 423–512.

———. 1976. Pseudodoxia Copernicana. *Archives Internationales d'Histoire Des Sciences* 26: 108–158.

Swerdlow, Noel, and Otto Neugebauer. 1984. *Mathematical Astronomy in Copernicus's De Revolutionibus*. New York: Springer.

Szczeciniarz, Jean-Jacques. 1998. *Copernic et la révolution copernicienne*. Paris: Flammarion.

Vesel, Matjaž. 2014. *Copernicus: Platonist Astronomer-Philosopher. Cosmic Order, the Movement of the Earth, and the Scientific Revolution*. Trans. Manca Gašperšič. Frankfurt am Main: Peter Lang.

Westman, Robert S. 2011. *The Copernican Question: Prognostication, Skepticism, and Celestial Order*. Berkeley/Los Angeles: University of California Press.