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Celestial Physics

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Introduction

In Platonic philosophy, there is a fundamental dichotomy between the intelligible and the sensible. The intelligible forms, immaterial and incorruptible, underlie the order ingrained in our material world. They are imbued with ontological necessity, whereas what transpires in the sensible world around us is characterized by contingency. This dichotomy is still present in Aristotle, only it has, as Pierre Aubenque wrote, become *physical*.[1] Aristotle offers the heavens as a realm of orderly and necessary motions, opposed to the mutability and contingency of the sublunar region. The concentric and uniform motion of heavenly bodies plays an essential role in Aristotelian natural philosophy and, indeed, ontology. But Aristotle's writings provide no technical astronomy for predicting the actual motions of heavenly bodies. Soon enough, Greek astronomy would introduce geometrical tools contradicting Aristotle. The crowning achievement of Greek astronomy, Ptolemy's *Almagest*, proposed an accurate planetary theory using non-concentric circles and a device called the equant. The equant, an innovation of the first order, was an elegant way to make the planets change speed in their courses. While Ptolemy's techniques gave excellent results, they clearly deviated from Aristotelian requirements: Ptolemy had the planets revolving around the Earth with eccentric, non-uniform motion. In the Islamicate Middle Ages and Latin Renaissance, there were major attempts to reconcile Aristotle's physical explanations with Ptolemy's mathematical descriptions. Yet a universally accepted synthesis never emerged.

According to standard narratives about the Scientific Revolution, Copernican heliocentrism demanded new physical explanations, both of the motions of the planets and of the behavior of bodies on a moving

[1] Aubenque (2005, 314).

Earth. These were ultimately achieved with the advent of Newtonian mechanics, which merged mathematical astronomy with physics. It dissolved the Aristotelian dichotomy, extending the ontological purity of the celestial region to all matter or, vice versa, bringing the corruptibility of terrestrial existence into the heavens. All bodies, from a star to a speck of dust in a current of air, were now presumed to follow the same laws.

These traditional narratives draw a direct, continuous line from Nicolaus Copernicus to Isaac Newton. Alexandre Koyré described Copernican astronomy as the crucial first step in the transformation of the closed cosmos of Aristotle to the boundless universe of Newton.[2] Thomas Kuhn similarly framed early modern scientific developments as a "Copernican Revolution," which subsequently became his paradigm, of sorts, for scientific *revolutions* in the plural.[3] There is, however, as Koyré and Kuhn would both concede, an enormous gulf of knowledge and technique between Copernicus and the Newtonians; the connection is not as direct as it might seem. In fact, Copernicus was not always considered a watershed figure. Auguste Comte, the founder of positivism, thought that Copernicus did little but offer an ancient theory without removing the principle obstacle standing in the way of its acceptance – i.e., the Aristotelian account of terrestrial phenomena. True heliocentric astronomy required Galileo and the invention of what Comte called a "rational mechanics."[4] Ernst Mach, from the perspective of the history of mechanics, almost totally ignored Copernicus, stressing instead the achievements of Johannes Kepler and Galileo Galilei in celestial physics and dynamics.[5]

In this chapter, we will consider how astronomers and natural philosophers of the sixteenth and early seventeenth centuries sought to unify mathematical astronomy with physical and metaphysical causes. In doing so, we will explore several related themes, much debated in the period: the order of the celestial bodies and their nature, the relationship between celestial and terrestrial phenomena, the question of celestial animism or vitalism, and the status of the divine in celestial nature. While focusing on the figures of Copernicus and Kepler, we will also touch upon a variety of thinkers with diverse methods and interests.

Early Sixteenth-Century Physics and Astronomy

In Scholastic natural philosophy, the heavens operate by rotating celestial spheres that carry the planets and stars. Medieval natural philosophy, both

[2] Koyré (1957). Also see Koyré (1965).
[3] Kuhn (1959); Kuhn (1962). See Omodeo (2016a, 61–86). [4] Comte (1835, 145–146).
[5] Mach (1988, 211–212).

Islamicate and Latinate, inquired into the nature of these celestial causes, which could be intelligences, angels, or souls. Mathematical astronomers, on the other hand, did not usually write about *how* the spheres turned, this being the province of philosophers and theologians, but there was wide consensus that they existed. This consensus carried on into the Renaissance.[6] Nevertheless, Ptolemaic astronomy relied on intersecting circular motions around many centers, which thus could not be straightforwardly attributed to solid spheres. Since the time of Ptolemy, some astronomers had argued that a system of partial, nested, eccentric spheres could reproduce Ptolemaic eccentrics and epicycles by way of non-intersecting three-dimensional bodies. Sixteenth-century university students typically learned such a system from Georg Peurbach's *Theoricae novae planetarum* (New theories of the planets) (1472), which systematized models developed by Islamicate astronomers and was widely adopted. Still, it preserved the philosophically problematic aspects of Ptolemaic astronomy: multiple centers and non-uniform motion produced by the equant. Nevertheless, the scheme could at least provide reassurance that Ptolemaic models might be reconciled to Aristotelian physics, at least in principle.

The inconsistency between predictive models and established natural philosophy periodically gave rise to dissension against Ptolemaic astronomy, and so against eccentric spheres. One episode featured the thirteenth-century Andalusian scholar Averroës (ibn Rushd), who insisted on the primacy of Aristotle's natural philosophy. Averroës identified the Aristotelian prime mover with the monotheistic God; separate intellects, he thought, animated each of Aristotle's celestial spheres.[7] In his commentaries on *Metaphysics* XII, Averroës asked astronomers to reject Ptolemaic models and ascribe planetary motions to concentric spheres instead, in accord with Aristotelian philosophy. Meanwhile, Averroës' contemporary, Alpetragius (al-Biṭrūgi), developed a complex theory of planetary motions guided by such principles.[8]

Early sixteenth-century celestial physics in Europe was marked by the convergent reception of Averroës and Alpetragius. Averroës' cosmopsychology was well established in universities by Copernicus's time – e.g., the philosopher Pietro Pomponazzi lectured on Averroës' *De substantia orbis* at Padua[9] – while a Latin translation of Alpetragius's *Kitāb fi'l-hay'a* was published in Venice under the title *Planetarum theorica physicis rationibus*

[6] Barker (2011). [7] Averroës (1986).
[8] For a brief overview of Islamicate critics of Ptolemy, see Evans (1998, 396–397); Morrison (2013, esp. 121–127).
[9] Pomponazzi (1966).

probata (Planetary theory demonstrated through physical proofs) in 1531. Paduan scholars took inspiration from their combined physico-mathematical program and created novel astronomical systems relying on homocentric spheres. The most prominent of these works were Giovanni Battista Amico's *De motibus corporum coelestium iuxta principia peripatetica, sine eccentricis et epicyclis* (On the motions of the celestial bodies according to peripatetic principles, without eccentrics and epicycles) (1537) and Girolamo Fracastoro's *Homocentrica sive de stellis* (Homocentrics, or On the stars) (1538).[10]

Copernicus can be situated within this tradition of astronomers attempting to harmonize astronomy with philosophical principles. The uniformity of celestial motions is fundamental to his physics and mathematical astronomy. While his commitment to uniformity may have been motivated by belief in the reality of celestial orbs, the clearest justification for uniformity given by Copernicus is metaphysical: irregularity could not be expected of these "objects constituted in the best order."[11] In any case, he did not think that his contemporaries' homocentric theories agreed with observations.[12] His *De revolutionibus orbium coelestium* (On the revolutions of the celestial spheres) (1543) deploys mathematical techniques in order to remove the more egregious irregularities attributed to the heavens by Ptolemy.[13] Copernicus's early readers recognized these ambitions and, in many cases, lauded his successes.

Copernicus, Mathematics, and Nature

In *De revolutionibus*, we see two features that are striking from the perspective of sixteenth-century natural philosophy. The first is an insistence that mathematical fittingness can say something conclusive about the structure of nature. The other is that Copernicus makes the celestial nature of the heavens a universal characteristic of matter.

[10] See Di Bono (1990).

[11] Copernicus (1543, 3^{r}); Copernicus (1978, 11). The consensus among historians of astronomy is that Copernicus had some commitment to the reality of celestial orbs. See Swerdlow (1973). For a still pertinent discussion of the controversy that surrounded this issue, see Jardine (1982).

[12] Copernicus (1543, iii^{v}); Copernicus (1978, 4).

[13] Copernicus used a minor epicycle to replace the equant. This technique is identical to one found in Ibn al-Shātir (1304–1375). In order to reproduce alleged variations in the rate of equinoctial precession, he used the Tūsī couple, which had been introduced by Nasīr al-Dīn al-Tūsī (1201–1274). Amico and Fracastoro had also both used the Tūsī couple in their homocentric systems.

Copernicus's mathematical models of uniform planetary motions have the shocking consequence that the Earth no longer stands at the center of the planetary order. But he emphasized the simplicity and interconnectedness of his heliocentric astronomy. With a mobile Earth, astronomers could calculate the size of planetary orbs, using the Earth–Sun distance as a yardstick. All the planetary distances could then be expressed as a series of interrelated ratios that he calls the world's "symmetry." In addition to symmetry, the heliocentric arrangement yielded a "harmonious linkage" (*nexus harmoniae*) between planetary distances and their periods: the longer the period of revolution, the longer a planet's path around the Sun.[14] This correspondence between period and distance was a well-accepted principle in geocentric astronomy, yet from a modeling point of view, geocentric astronomers could order the planets however they liked.[15] By contrast, in *De revolutionibus*, the period–distance relationship proves necessary. The new order, Copernicus argues, also explains planetary phenomena that otherwise seem unrelated to one another, like the peculiarities of retrogradation (especially the relationship between retrogradation and a planet's opposition or conjunction with the Sun).[16] Many details in Ptolemaic theory work without any underlying reason; the astronomer just has to follow the rules. Copernicus saw these details as clues leading to the Earth's motion as a common cause. What we find in *De revolutionibus* is an astronomer showing how mathematics, or *mixed* mathematics, describes the structure of nature over and above the conclusions of natural philosophy or "physics" (as it could also be known). To put it another way, Copernicus yokes physics to astronomical demonstration, which he values according to a certain conception of elegance or fittingness.

The geometrical order that Copernicus celebrated put him in contradiction with Aristotelian physics when it came to explaining terrestrial phenomena. Aristotle's robust theory of sublunary elements and their motions both depended upon and supported the centrality and immobility of the Earth – in particular, Aristotle explained that the four Empedoclean elements (earth, water, air, and fire) naturally move rectilinearly toward or away from the unique and immobile center of the world. Copernicus also had to deal with the basics of experience. In the *Almagest*, Ptolemy had described some of the

[14] Copernicus (1543, 9^{v}–10^{r}); Copernicus (1978, 22). For Copernicus's use of *symmetria*, see Hon and Goldstein (2008, 157–163).

[15] Aristotle uses this principle to establish planetary distances in *De caelo* II.10 (291a29–291b10) (Aristotle 1984, 1:480).

[16] For a list of technical points that Copernicus saw as confirming his astronomy, see Swerdlow (2004, 88–90).

phenomena that would presumably follow from the diurnal rotation of the Earth: for instance, a roaring westward wind, caused by the Earth turning at high speed beneath the air.[17] The obvious lack of such phenomena spoke against Copernicus's view. In addition, the absence of stellar parallax meant that the Earth–Sun distance was negligible compared to the distance from the Earth to the fixed stars. His astronomy implied that the universe was unfathomably large.

In response, Copernicus embraced this new cosmic vastness, although he left it to philosophers to decide whether the universe was truly infinite. Copernicus offered some sketchy physical arguments to convince his readers that terrestrial motion was actually possible. His answer for why we do not perceive the Earth's motions is that we participate in them. He invoked the now-famous analogy with a moving boat in which the passenger cannot immediately tell if the shore is slipping away from the boat or the boat from the shore.[18] Copernicus also emphasized a point of similarity between the terrestrial and celestial bodies: they are spherical. Of course, for Aristotle, the perfectly smooth heavenly spheres were much more exactly spherical, but Copernicus subverts this position by making the Earth the standard of spherical perfection – calling it an "absolute" sphere. He asks readers to consider the Earth as a geometrical whole; although our landscape is full of elevation changes, these discrepancies are negligible compared to the overall size of the globe.[19] Ancient mathematicians had established the Earth's almost perfect sphericity, but Copernicus draws on the latest geographical discoveries by Christopher Columbus and Amerigo Vespucci for evidence that the elements of earth and water share the same spherical surface (something that Ptolemy had argued for in his *Geography*).[20] Given that the celestial bodies are spheres, and given that they undergo circular revolutions, we should not then deny the Earth its own revolutions. This might not demonstrate any kind of physical necessity, but it argues that terrestrial motion is not physically *impossible*.

As for how this is physically *possible* – how the Earth can maintain its own center, despite its varied motions – Copernicus is not especially clear. He says that the matter of a planet holds together in a sphere through some natural desire (*appetentia*), implanted by God, to unite with its own kind.[21] In turn, the Earth's motions are shared with all of its constituent bodies. Note that this account obviates any dependence on a fixed center of the world. Copernicus

17 Ptolemy (1998, 45). 18 Copernicus (1543, 6^{r}); Copernicus (1978, 16).
19 Copernicus (1543, 1^{r-v}); Copernicus (1978, 8–9). 20 See Vogel (2006, 480).
21 Copernicus (1543, 7^{r}); Copernicus (1978, 18). See Hooykaas (1987); Knox (2005).

also reframes all rectilinear motion as inherently violent. There is only one natural motion: circular revolution. Hence, Copernican physics "celestializes" the terrestrial, such that the motion of celestial bodies becomes the shared motion of all things.

Copernicus's appeal to an inherent *appetentia*, however vague, seems to have been inspiring. Early defenders of terrestrial motion like Celio Calcagnini, around 1518, and later Giordano Bruno, William Gilbert, and Kepler saw terrestrial motion as dependent, fully or partially, on celestial animation, the position that some or all celestial bodies were equipped with souls. Kepler observed that, "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 [*una et eadem anima motrice informari*], which, while rotating the Earth, also rotates those particles cast away from it."[22]

Renaissance Vitalism and the Fluid Heavens

From Greek philosophy through to its medieval Arabic and Latin commentators, the celestial bodies were thought to be alive or moved by separate intelligences. In Scholastic philosophy, the latter option was much preferred. The idea of stars and planets endowed with souls struck too pagan a chord and conflicted with widely held views on God's rule over nature.[23] In the sixteenth century, though, life came flowing back into the cosmos. Indeed, innovative cosmologies of the period were supported by an appeal to vital causes in the heavens. For example, the same Fracastoro whose *Homocentrica* was a counterpoint to Copernicus participated in this vitalist turn. He had debated the causes of celestial motions as early as 1531, and his readers asked for a more thorough investigation of the causes. Among them, the Venetian intellectual Gasparo Contarini invited Fracastoro to revive the doctrine of *Metaphysics* XII in order to provide a solid foundation on which to ground celestial motions in accordance with Aristotelian commentators such as Averroës and Alexander of Aphrodisias.[24] In the event, Fracastoro adopted a different physics entirely. In *Fracastorius, sive de anima, dialogus* (Fracastoro's dialogue, or On the soul) (posthumously published in 1555), he regarded planets as animal-like bodies whose souls are akin to the world-soul (*anima mundi*), which infuses life and motion throughout all parts of the universe.

[22] Calcagnini (1544); Kepler (1937, 3:28); Kepler (1992, 58–59).
[23] See Dales (1980); Grant (1994, 469–487). [24] Contarini (1571, 238–252, esp. 240).

Because planets derive their powers from the world-soul, their vital and intellectual faculties are rooted in nature and do not presuppose separate intelligences, *pace* Averroës.[25]

Fracastoro's natural philosophy owes a complex debt to Marsilio Ficino.[26] A principal textual source behind the sixteenth-century animation of the heavens was the reintroduction of Platonic and Neoplatonic philosophy through Ficino's translations and commentaries.[27] His *De vita libri tres* (Three books on life) (1489) – particularly its third book, *De vita coelitus comparanda* (On obtaining life from the heavens) – proved extremely influential on an important cross-section of natural philosophers, making the twin concepts of cosmos-infusing *anima mundi* and *spiritus mundi* philosophically attractive. The wider point is that explanations of natural phenomena, including those in the celestial realm, began to appeal to various kinds of non-Aristotelian natural philosophy, as well as non-literal forms of Aristotelianism. Most significantly, whereas in the first half of the sixteenth century, there was a more or less uniform acceptance of corporeal celestial spheres,[28] during the second half, a rival view achieved wide acceptance – that of an open, fluid heavens through which the celestial bodies move freely.

The first known measurement-based refutation of solid spheres came in 1557 from Jean Pena, who concluded in a Stoic vein that the entire universe must be filled with the same air that envelops us.[29] Pena's work influenced the astronomer Christoph Rothmann, who in turn played a role in the development of Tycho Brahe's conclusions about the composition of the heavens.[30] Brahe's renowned treatise, *De mundi aetherei recentioribus phaenomenis* (On the more recent phenomena in the ethereal world) (1588), was the most influential affirmation of heavenly fluidity. In it, he reviewed the debates and publications on the comet of 1577–1578, established its parallax and distance, and concluded that its location was above the Moon, in the space once deemed to be occupied by incorruptible material spheres. Since the comet freely moved there, the superlunary region had to be fluid. With the absence of solid spheres, however, it became urgent to establish the cause of planetary motion.[31] Brahe resorted to a "science infused by God" in the celestial bodies, governing their free motion through space.

[25] Fracastoro (1574, 149^{v}–150^{r}). [26] See Pennuto (2008, 7, 12).
[27] See, for example, Hankins (1999).
[28] On the material characteristics of solid spheres in the medieval period, see Grant (1987a, 172–173).
[29] Barker (2008, 273–274).
[30] Rothmann (2014). Also, see Goldstein and Barker (1995); Mosley (2007, 77–78).
[31] Granada (2010).

Other scholars who accepted heavenly fluidity or vacuum also ascribed souls to the planets capable of motivating their motions. Among them, the Neoplatonic thinker Francesco Patrizi revived the Stoic image of the planets moving themselves through the fluid heavens like fish in water and birds in the air.[32] In a much different philosophical framework, the Copernican heretic Bruno defended a similar view of the planets moving through an infinitely expansive aether.[33] Bruno's framework was marked by an idiosyncratic kind of atomism and by a forcefully argued position that God's essence implied a universe without boundaries or any privileged center. In his many philosophical works, Bruno asserted a boundless, living universe occupied by countless *synodi ex mundis*; that is, heliocentric planetary systems encircling each star.[34] For Bruno, the celestial bodies are big animals, endowed with sensible and rational souls governing their organic functions and movements. Specifically, heavenly bodies move through space in order to make the exchange of life and warmth between fiery suns and cold earths possible.[35] The English physician and philosopher William Gilbert, who maintained interplanetary space to be a vacuum – a very rare opinion – would later hold a similar view about the Earth's diurnal revolution.[36] Kepler, who believed space to be filled by a tenuous aether, would also consider the celestial bodies alive (although not intellective), thereby accounting for the production of celestial forces on which to base his new astronomy. He would also speculate about the nature and activity of the the Sun's soul as a kind of world soul, generating with its warmth new stars and comets in the celestial reaches.[37]

Kepler's Natural Theology and Celestial Physics

Kepler, Imperial Mathematician to the Holy Roman Emperors Rudolf II and Matthias, justly occupies a central place in the history of celestial physics. He was in many ways typical of the reception of Copernicus. He connected the new astronomy to the divine and sought to create for it a plausible natural philosophy. But he was in other ways singular. He argued in detail for a method of discovery and confirmation that intertwined mathematical and physical considerations; wherein geometrically equivalent astronomical models could be compared via their physical consequences.[38] His physics made no distinction between celestial and terrestrial – we can understand celestial matter and forces by examining objects at hand. His physics,

[32] Rosen (1984). [33] Grant (1981, 188–189). [34] Granada (2007).
[35] Bruno (1962, 81). See Gatti (1999, 121). [36] Gilbert (1958, 224).
[37] For Kepler's vitalism, see Boner (2013). [38] See Jardine (1984); Martens (2000).

informed by his mastery of optics and mechanics, was also highly mathematized, emphasizing the quantification of bodies, distances, and spatial orientation. For example, he believed that the force of the Sun was related to its mass and density.[39] Consequently, Kepler pushed the reform of astronomy much further than any of his peers, basing it on physical causes and granting it authority to speculate about matter and force.

Kepler's work was rooted in a specific natural-theological context. The Reformation philosopher Philipp Melanchthon, an architect of Lutheran higher education, taught his pupils that the celestial motions reveal God's wisdom and exert a providential influence on the sublunary realm. At the University of Wittenberg, where he was professor, Melanchthon promoted natural philosophy, the mathematical arts, and medicine, as so many ways of witnessing God's presence and wisdom.[40] Melanchthon used his institutional authority to promote the careers of the mathematicians Georg Joachim Rheticus and Erasmus Reinhold. Rheticus became the disciple of Copernicus and authored the *Narratio prima* (First account) (1540), the first published exposition of Copernican astronomy. It was also Rheticus who spearheaded the publication of Copernicus's *De revolutionibus*. Reinhold reintegrated Copernican innovations within a geocentric framework and used Copernicus's models to calculate his *Prutenic Tables*, soon the most widely used astronomical tables in Europe. Reinhold's reception of Copernicus – taking the mathematics while passing on the physics – typifies what the historian Robert Westman named "the Wittenberg interpretation of Copernicus."[41] Unsurprisingly, Melanchthon's own reception of Copernicus was complex. At first, he violently rejected the physics on Ptolemaic, Aristotelian, and, most importantly, biblical grounds. But he listened to his mathematician colleagues enough to eventually appreciate the technical innovations of Copernican astronomy, as well as what he took to be its eschatological implications. Copernicus had asserted in Book III of *De revolutionibus* that the eccentricity of the Sun was steadily diminishing. Melanchthon seized on this, seeing it as a sign of the approaching end times and return of Christ.[42]

Kepler, educated at the University of Tübingen, was a product of the Melanchthonian program. At Tübingen, where he was studying for the Lutheran priesthood, he had the good fortune to learn astronomy from the mathematics professor Michael Maestlin, an eminent astronomer and

[39] Regier (2014). [40] Kusukawa (1995). [41] Westman (1975); Westman (2011, 150–164).
[42] Lerner (2006, 442–444).

one of Europe's few convinced Copernicans. Kepler firmly believed that our world was a unique creation bearing everywhere the stamps of the divine mind. The cosmos had to be ideally structured and singular. He also believed that the ideas behind the world's creation – the blueprint, as it were – had to be within the bounds of human comprehension. Kepler thus criticized the thesis of an infinite universe – particularly in *De stella nova* (On the new star) (1606), *Dissertatio cum Nuncio sidereo* (Conversation with the sidereal messenger) (1610) and *Epitome astronomiae Copernicanae* (Summary of Copernican astronomy) (1618–1621) – not just because he saw it as an expression of Epicurean impiety.[43] It threatened to make the structure of our planetary system – the best possible structure – redundant, unnecessary, even unintelligible.

The goal of Kepler's first published book, *Mysterium cosmographicum* (Cosmographical mystery) (1596), was to justify Copernican astronomy, taking as seriously as possible Copernicus's promise that his astronomy brought us closer to the divinely conceived structure of the world. Since the Earth's movement made it possible to calculate the sizes of the planets' orbits, Kepler sought to explain why they are endowed with certain sizes and not others. He professed to demonstrate the reason why through the Platonic solids; i.e., the five regular polyhedra. These solids could be interposed between the planetary paths to arrive at a system of proportions yielding (approximately) the Copernican distances. Part of the solution's appeal was the use it made of mathematical objects charged with value. The solids have a world-building role in Plato's *Timaeus*, where they serve as the forms of the elements, and they are also the subject of the last book of Euclid's *Elements*.[44] Kepler could offer his discovery as an unearthing of lost ancient wisdom, even suggesting that Pythagoreans had once known the cosmic function of the Platonic solids but had kept their secret from outsiders.[45] Kepler's archetypical reflections culminated in *Harmonice mundi* (Harmony of the world) (1619). Here, he combined several metaphysical elements into a single coherent world system: the polyhedral hypothesis of the *Mysterium*, which explained the planets' distances to the Sun, was combined with Kepler's own theory of harmony to explain their motion. All of this was fitted to a long meditation, heavily indebted to Proclus, on the geometrical nature of

[43] Boner (2007).
[44] Kepler described both the *Timaeus* and *Elements* as "Pythagorean" works. In fact, he saw Euclid transmitting in his *Optics* "a pure unadulterated Copernican astronomy" (Kepler 1937, 3:284–287; Kepler 2000, 342–345).
[45] Kepler (1937, 6:81); Kepler (1997, 115).

souls, their relationship with the divine, and their instinctive mathematical knowledge.[46]

Kepler's theological-harmonic speculation had important predecessors in fifteenth- and sixteenth-century scholars who had embraced the Platonic idea of cosmic harmony.[47] Rheticus, Copernicus's disciple, had written that heavenly symmetry and harmonious linkage are best understood through an immediate apprehension of the mind rather than by language: "not so much by words as by the perfect and absolute ideas, if I may use the term, of these most delightful objects."[48] Girolamo Cardano, one of the most original philosophical and mathematical intellects of the sixteenth century, had formulated a program belonging to a geometrical style of thought similar to Kepler's. In his *Encomium geometriae* (Praise of geometry) (1535), he affirmed, without going into detail, that one could reconstruct the secret proportions of creation assuming that God, the greatest geometer, had constructed the cosmos according to proportions derived from the internal structure of geometrical figures. According to Cardano, one could unveil the ratio of the distances of the seven planets by following such a divinely inspired construction method.[49]

Kepler's quest to unveil God's construction of the world also led him to seek the active causes by which the heavenly motions are produced, principally the interaction between Sun and planets. This produced Kepler's now most famous treatise, significantly titled *Astronomia nova ΑΙΤΙΟΛΟΓΗΤΟΣ seu physica coelestis* (New astronomy from the causes, or celestial physics) (1609).[50] *Astronomia nova* rested on highly accurate observations made by Brahe together with his team of assistants. Framing his work as a narrative of struggle and discovery, Kepler demonstrated that planetary orbits are ellipses with the Sun occupying one of the foci (later known as Kepler's "first law"), that from the Sun emanates a moving force, and that, consequently, planetary speed changes in a calculable way as the planet's distance from the Sun increases or decreases (according to what has later become known as the "second" or "area law"). Kepler expected his astronomical models to describe physical causes – real bodies and real forces. For instance, the area law worked, according to Kepler, because the areas in question represented infinitely many moments of impulsion radiating from the Sun.[51] For his

[46] For Kepler's harmonies, see Walker (1967); Stephenson (1994).
[47] This along a line traced from Ficino's reflections on the *Timaeus*. See Prins (2015, 80–118).
[48] Kepler (1937, 1:104); Rosen (1939, 145). [49] Cardano (1966, 4:445b).
[50] For a thorough discussion of Kepler's astronomy and its physical grounding, see Stephenson (1987); Voelkel (2001); Davis (2003).
[51] Aiton (1975a); Aiton (1975b).

conception of the solar force, he drew inspiration from Gilbert's *De magnete* (On the magnet) (1600) and concluded that the Sun was a magnetic body. Later, in the *Epitome astronomiae Copernicanae*, he enlarged his theory of planetary motion to include magnetic filaments in the planetary bodies. Kepler's project to explain celestial motion by natural forces did not stand in contradiction with his thoughts on celestial souls. He felt that his physical astronomy made *intellective* souls unnecessary in the heavens. But he still believed animal souls were needed to account for generation and active forces in nature. Souls remained, for Kepler, the motors of nature.[52]

Alternative Programs

Kepler's celestial physics left many discontented, including Brahe's pupil Christianus Severinus Longomontanus, professor at Copenhagen, who attacked Kepler's novel approach because it infringed on accepted disciplinary distinctions between metaphysics, physics, and mathematical astronomy. He accused Kepler of impiety since the latter reduced celestial *meta*-physics to mere celestial physics.[53] Longomontanus's *Astronomia Danica* (Danish astronomy) (1622) can be considered the apex of the geometrical tradition in astronomy, which modeled planetary motions by means of epicycles in the geo-heliocentric framework that Tycho Brahe had claimed as his own invention and vigorously promoted. In this framework, the Earth remains immobile; the Sun circles the Earth, and the planets circle the Sun. One of the obvious advantages of such a combination concerned sublunar physics, since it secured the central and immobile position of the terrestrial region. Moreover, it maintained the key postulate of Scholastic celestial physics: that is, perfect celestial bodies follow laws that differ from those governing terrestrial matter.

Likewise, Daniel Cramer, a professor of the Stettin Gymnasium, had discussed these issues with Brahe and suggested a manner in which geo-heliocentric, fluid-heaven astronomy could and should be reconciled with Aristotle's *Metaphysics* XII. Cramer dedicated to Brahe an *Isagoge in Metaphysicam Aristotelis* (Introduction to Aristotle's *Metaphysics*) (1594 and 1601), in which he discussed the causation of celestial motions. According to Cramer (who was followed by several Baltic astronomers), one could resort to the separate intelligences of the Averroist tradition and apply them

[52] For the role of solar soul in Kepler's late astronomy, see the *Epitome* (Kepler 1937, 7:298–299).

[53] Longomontanus to Eichstaedt (Copenhagen, June 6, 1638), in Eichstadius (1644, 148, 151).

directly to the bodies of the planets, instead of to non-existing celestial spheres.[54]

Kepler was not unprepared for such criticism, arguing in response that no causal account could explain how the massive body of the Sun might circle the Earth.[55] As for religious concerns, he stressed that Copernican astronomy was better suited to Christian faith. The uniqueness of the source of heavenly motions, firmly located at the center of the world in the Sun, mirrors the uniqueness of its creator; by contrast, the separate celestial intelligences, which late-Scholastic Tychonians (like Cramer) embraced, seemed to revive the polytheism implicit in Aristotle.[56] Nevertheless, Kepler's objections discouraged neither his Protestant opponents nor Jesuit neo-Thomists from working within a geo-heliocentric paradigm, as witnessed in the Italian reception of Brahe by Christoph Clavius and Giovanbattista Riccioli in the seventeenth century.[57]

Mechanical objections to Kepler's physics were of a different tenor. In the fourth day of the *Dialogo sopra i due massimi sistemi del mondo* (Dialogue concerning the two chief world systems) (1632), Galileo mocked Kepler's explanation of sea tides based on the distant action of the Moon upon the waters. Instead, he developed the thesis of his Pisa professor, Andrea Cesalpino, that the tides were produced by the combination of the Earth's diurnal and annual motions. In fact, Galileo treated this explanation of the tides as the strongest argument in favor of Copernicanism. Giovanni Pico della Mirandola's criticism of astrology and occult virtues loomed large in Cesalpino's and Galileo's rejection of lunar influence.[58] Anti-astrological skepticism cast into doubt the very foundations of Kepler's celestial physics, even if Kepler had largely followed Pico's restrained view of celestial causes.[59]

More generally, the rejection of action at a distance and final causes became two tenets of seventeenth-century mechanist philosophies. Their alternative programs envisaged a physics resting on a small set of laws governing bodily motions and interactions *everywhere*. Pierre Gassendi, heavily involved in astronomy throughout his career, drew from Kepler's theory of a magnetic Earth, but while Kepler had been adamantly anti-Epicurean, Gassendi reimagined the magnetic filaments as atoms causing our diurnal rotation.[60] René

[54] Omodeo (2016b). [55] Kepler (1992, 169–170). [56] Omodeo (2015).
[57] Lerner (1995).
[58] Omodeo (2017).
[59] For Kepler and Pico, see Rabin (1997). For Kepler's astrology, see Field (1984).
[60] Sakamoto (2009).

Descartes similarly rewrote physics according to a new corpuscular conception of the world. In his *Le monde* (The world) (written before 1633 and first published in 1664) and in the *Principia philosophiae* (Principles of philosophy) (1644), he defended the vision of an indefinitely large universe bearing significant resemblance to Bruno's as to its overall structure, but not as to its principles. For Descartes, celestial bodies do not autonomously move owing to an inner impulse, as Renaissance vitalists had claimed. Rather, they are transported by fluid vortices of subtle ethereal matter. Moreover, he took cosmological homogeneity much further than his Renaissance predecessors; for him, the corruptibility of the heavens implied that stars could become comets and that comets could then transform into planets.[61] These trends reached their climax with the work of Newton, whose *Philosophiae naturalis principia mathematica* (Mathematical principles of natural philosophy) (1687) synthesized celestial and terrestrial physics into a unified system of gravitational interactions between bodies. Notably, Newton's gravitation retained the flavor of Kepler's attraction at a distance, even if Newton avoided explicit commitment to any causal explanation of gravity.

Concluding Remarks

We would stress that the achievements of sixteenth- and early seventeenth-century cosmology were ultimately due to the remarkable liberties available to astronomers. Thanks to humanism and printing, many causal frameworks were available. Political and social contexts, which fall outside the purview of this chapter, also played an undeniable role. It has long been understood that opportunities of court patronage gave figures like Brahe, Kepler, and Galileo, distinct intellectual freedom over most university professors. A patron like Rudolf II, the Holy Roman Emperor, expected novelty; his Imperial Mathematician, Kepler, was ready to provide it. Of course, intellectual freedom is never total. It is always contingent on local powers, as the fates of Bruno and Galileo remind us. If the celestial revolution was lasting, it was for the following reason: our vision of the heavens underwent such a variety of transformations during the sixteenth and seventeenth centuries, and in such a variety of contexts, that by the end, short of almost inconceivable tyranny or social collapse, it would have been impossible to return to the cosmos taught at the close of the fifteenth century. Here is perhaps

[61] Aiton (1972).

the sense in which we might best understand this intellectual revolution: at a certain point, it became impossible to reverse direction on so many byways and avenues that may have, over the short term, once allowed two-way traffic.[62]

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