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Introduction

It's fixed, the Scriptures say. And so
Orthodox science proves.
The Holy Father grabs its ears
To show it's firmly held. And yet it moves.
—Brecht, *Life of Galileo*

Eppur si muove! And yet it moves!—the sentence is too good to be true. Supposedly muttered by a defiant Galileo Galilei after being forced by the Catholic Inquisition to renounce heliocentrism, the astronomical model that has the earth revolve around the sun, it was destined to become the most famous in modern cosmology. Although Galileo never said such a thing, it came to stand for the replacement of the Ptolemaic worldview by Copernicanism, a clarion call for the superiority of knowledge over faith. Like a historical divining rod, it marks the moment when science broke free from the precepts and prejudices of religion to pursue its own creed, the uncompromising search for truth.

As with all foundation narratives, there is much that is mythically stylized about this one. Religion did not rule out the search for truth, and there was more to the Galileo affair than a supposedly head-on collision between truth and power, as has been claimed ever since. Still, the story shows that the question of the earth's rotation involved more than an exchange of arguments ending in a simple yes or no. It became a test case for the weighty problem of order in the cosmos and the place occupied by humankind in that order. *What can I know? What may I hope?* Immanuel Kant's fundamental questions still strike us today as an echo or aftershock of the seismic shift brought about by Copernicus. On the one hand, the Copernican reform posed the question of whether we occupy a fixed point at the center of the universe or dwell somewhere on its periphery and orbit the sun. On the other, it raised a pressing epistemological concern: to what extent have we been endowed with senses and reason to hope to believe and want to know anything in the first place? Both aspects contained anthropological dynamite, for geocentrism could draw on an intimate alliance between sense and sensation that heliocentrism destroyed without offering any new metaphysical assurances to take its place.

Friedrich Nietzsche once remarked that Copernicus was the "greatest, most successful opponent of optical evidence" because he "convinced us to believe, contrary to all our senses, that the earth does not stand still."[1] Seventeenth-century natural scientists knew just as well as Nietzsche that the senses were not always trustworthy, but pointing out the unreliability of the seen did not automatically justify faith in the unseen. How, then, were early Copernicans such as Galileo or Johannes Kepler supposed to convince skeptics that the sun did not really rise in the east and set in the west? How were they to explain that despite the earth's double movement around the sun and on its own axis, humans still stood with their two legs planted firmly on the ground without being overcome by vertigo or flung into outer space as from a spinning top? Catholic orthodoxy demanded hard evidence. Roberto Bellarmino, Galileo's Jesuit antagonist, who had already played a sinister role in the trial of Giordano Bruno, claimed that the church was prepared to reconsider its position if proof of Copernicanism were offered. There is no way of knowing whether the seventeenth-century church would have honored its word, but the fact that Bellarmino even contemplated such a revision indicates that Galileo's apocryphal utterance—*And yet it moves*—had arguments, if not optical evidence, on its side.

In the seventeenth century, experimental evidence of the earth's rotation would have been a triumph for Copernicanism, a final piece in the puzzle that would have completed the new picture of the universe. Yet despite many attempts, no such proof was forthcoming. Galileo even risked the categorical declaration that no such proof could be made on earth[2]—and he would not be proven wrong for another two hundred years. The fact that heliocentric cosmology nonetheless came to prevail over the course of a few brief decades in the seventeenth century has to do with a fundamental, much-discussed shift in mentality that prioritized empirical inquiry—observation, experimentation, and collection as the basis for knowledge of the natural world—but also established the mathematization of nature as an object whose mechanisms could be abstracted into universal physical laws. Galileo had already emphasized that the book of nature was written in the language of mathematics.[3] Isaac Newton then provided Copernicanism with a stable framework that allowed the earth's rotation on its own axis to be postulated as an indispensable, albeit not directly demonstrable, theorem. In the age of enlightenment, the need to prove the earth's rotation was shelved with rational austerity, even if isolated experiments yielding no conclusive results continued to be made.

The Copernican order had relegated humankind to the margins of the universe. According to Sigmund Freud, this signified the first of three blows to human narcissism, although by the mid-nineteenth century, shortly before the second blow was inflicted by Charles Darwin, its impact had been partly overcome.[4] In 1851, when Léon Foucault successfully made the earth's rotation visible with his pendulum experiment, he caused quite a stir, even though the need to furnish visual proof for Copernicanism had long since receded. Nobody, not even the Catholic Church, still disputed that the earth rotated. And philosophy, which otherwise claimed responsibility for questions of worldview, had moved on to different topics. Recovery from the blow of Copernicanism did not mean, however, that this experiment was simply registered as a well-designed mechanical apparatus that had no bearing on questions of human self-understanding.

Foucault's pendulum epitomized the ability of modern physics to produce an elegant, easily comprehensible experiment that vividly demonstrated the validity of natural laws. It promised to deliver the optical evidence highlighted by Nietzsche in a manner accessible even to the untutored eye. Ever since, this emphatic experiential moment has formed the focal point of the pendulum's public history, notwithstanding Nietzsche's skeptical objection that what strikes us as wonderful and marvelous in the movements of the planetary spheres has nothing to do with perception, instead lying "entirely in the mathematical strictness and inviolability of our representations of time and space."[5]

Nietzsche never directly addressed Foucault's pendulum, yet his insistence on dry mathematical abstraction, as opposed to the first-hand observation of cosmic processes typified in nineteenth-century popular astronomy, points to a fundamental aspect of the anthropological status assigned to the modern exact sciences following the triumph of Copernicanism: there is an abyss between human and cosmic existence that can be bridged only by the mathematical operations with which we seek to grasp nature. This gives rise to new difficulties, for while anyone can follow the phenomenology of the pendulum, the same cannot be said of the mathematics behind the phenomenon. With Hans Blumenberg, we could say that the experience (*Erlebnis*) paves the way for the result (*Ergebnis*).[6]

This ineradicable difference has consequences for historical analysis, given that the polarity between mathematics and sense perception also defines the history of the pendulum. On the one hand, the pendulum experiment belongs in the history of physics and astronomy, and the role it plays there cannot be understood without the mathematical details ordinarily taught in physics textbooks. On the other, it looms large in the history of the public presentation of science. The role it plays there cannot be grasped in isolation from its cultural, political, and aesthetic context. A more or less comprehensive history of Foucault's pendulum would subject both sides to critical scrutiny. So far as I am aware, no such investigation has been attempted, and my book also makes no claim to describe the physical and mathematical details of planetary orbits, the earth's rotation, the Coriolis force, or how the pendulum's behavior is affected by its latitude. Nor does it offer an exhaustive history of the various attempts to prove the earth's rotation. All this lies outside my expertise, and fortunately, we can draw on a series of studies in the history of physics that work through such details.[7]

The other side of Foucault's pendulum—its impact on discussions about human self-understanding and its repercussions for questions of politics and publicity, society and spectacle—has received far less systematic attention from the history of science.[8] In what follows, I will address this aspect and examine the historical constellations in which the pendulum was set in motion and disassembled, admired and discussed, illustrated and described. All this gives rise to a fundamental question: How could a scientific experiment proving a theorem that had long since been universally accepted not only create a sensation at its first public unveiling, but have lost none of its fascination in the more than one and a half centuries since? One possible answer is that while the experiment always and everywhere produces identical results, the *(re)presentation* of the pendulum has undergone constant change since Foucault's day. What are we to make of this? On their own, neither unvarying sameness nor constant change can attract and sustain public attention, certainly not over such a long period of time. My key argument will therefore be that precisely in its tension between physical invariance and historical mutability, the pendulum has repeatedly raised questions that go to the heart of our understanding of what it means to be human. Who is doing the seeing here? And what do they see when they see? These questions emerged with

Copernicanism, yet in Western culture, they have lost none of their anthropological relevance since we learned to come to terms with our cosmic marginality. They inform the history of the pendulum from the first to the most recent installation.

To begin with, there is the physical phenomenon itself, which always produces the same result in the same place at different times. Day in, day out, a Foucault pendulum oscillates beneath the dome of the Panthéon in Paris. As you enter the building, you see a metal bob hanging from a sturdy wire cable. A stylus protrudes from the underside of the sphere as it swings over a metal plate, surrounded by a ring marked in degrees. If you position yourself so that the metal ball is swinging straight toward you, and if you watch it long enough from this standpoint, you will notice it start veering to the left, in a clockwise direction, as can easily be read off the graduated ring. After around thirty-two hours, your sleep-deprived eyes will see the pendulum swinging back toward you, just as it had at the start of your vigil. What the uninformed observer cannot know is that the time taken for a complete rotation of 360 degrees depends on the latitude of the site where the pendulum is set in motion: thirty-two hours in Paris, Munich, or Vienna, twenty-four hours at the North Pole, no change in the oscillation plane at the equator. South of the equator, the latitude-dependent changes begin again, only this time in the opposite direction. I will come back to these differences later.

For now, I note that what visitors in the Panthéon are observing is not the pendulum moving in a circle, but the earth rotating beneath it. They are confronted with the counterintuitive fact that they are the ones who are moving, along with the ground beneath their feet, while the pendulum continues unwaveringly on its course. Far from modeling the earth's rotation, the experiment is itself a part of the cosmic process it illustrates. That the experiment that makes the process visible is *also* an ingenious feat of technical construction does nothing to contradict this. At the start, the bob is usually held in a sling that is then burned through by a flame to prevent it veering off course when released. Even minor deviations can make the experiment unworkable. The bob cannot be allowed to rotate and slip into an elliptical movement, making it wobble like a slowly turning top. For that reason, drafts caused by heaters, fans, or open doors must be avoided. Despite such precautions, disruptive forces cannot be eliminated, only minimized in their effects. In recent times, this is done with a so-called Charron Ring, positioned beneath the pendulum mounting and named after the French physicist Fernand Charron. The cable passes through this ring, limiting its movement as it swings backward and forward, thus reducing the risk of ellipsoidal precession.[9] It is important that the cable presents minimal aerodynamic resistance. The bob's center of gravity should ideally coincide with its midpoint. Finally, an electromagnetic impulse ensures that the pendulum maintains its amplitude and does not stop swinging, having to be manually restarted.[10]

A glance at its technical settings thus reveals a precision experiment typical of the physics of the time (leaving aside the Charron Ring, which was not introduced until later). Along with mechanical objectivity and statistical probability, precision was one of the most important nineteenth-century epistemic practices or norms by which the natural sciences asserted their knowledge claims. Even more importantly, precision was the indispensable precondition for producing instruments, tools, and technical equipment that went on to conquer diverse areas of science and the economy, extending all the way to the military and pleasure industries.[11] In contrast to other precision instruments, Foucault's pendulum was no "monnaie mécanique" (Claude Navier),[12] no machine for pumping out money on an industrial scale, notwithstanding the efforts of some enterprising showmen to charge entry for public demonstrations. Nonetheless, the symbolic value of the pendulum was great enough for it to be exhibited at the 1855 International Exposition in Paris.

Precision is thus the key to understanding why this experimental setup was ideally suited to demonstrating the apparent change in the pendulum's swing in time and space. This change can be observed, as mentioned, when the pendulum moves in a clockwise direction. Yet because the pendulum, suspended from a simple mount, does not move along with the earth, it follows that the entire space, including the spectator, must be rotating around the pendulum. While the suspension of the pendulum cable rotates with the earth, as does the ceiling to which it is attached, the plane of oscillation does not. This phenomenon defied explanation so long as the earth was assumed to be stationary, but even after Copernicus, Kepler, and Galileo, it continued to play no role. Despite Foucault's great discovery, this much remains true: although no one would deny that the earth turns counterclockwise beneath the pendulum, seeing the experiment can still be a mildly disorienting experience. Imagine a clock where the hand stays in place while the clockface turns.

The pendulum has been set in motion all over the world, and if reports are to be believed, it has everywhere provoked astonishment and fascination. It thus cannot be claimed that the viewer's specific experience of the pendulum depends on where the demonstration is held. The pendulum and its setting are mutually reinforcing. This also means that the varying historical constellations in which the pendulum is displayed are relevant for understanding it. Ever since it was first presented, political and aesthetic perspectives have played a role that is out of keeping with a demonstration in a physics lecture theatre.

Political: only a few weeks after Foucault's first trials, French president Louis-Napoleon Bonaparte, later crowned Emperor Napoleon III, authorized a public display of the pendulum in the Panthéon, a complex and contested building initially built as a church and then repurposed as a secular temple. Whether intentionally or not, Foucault thereby created the historical foundation for a Parisian tradition, even though a pendulum would not be permanently installed in the Panthéon until the late twentieth century. The first public exhibition proved eminently compatible with a broader public-relations campaign designed to demonstrate that progress in modern society was based on science and technology. However much ideological conflict between monarchists and republicans, Catholics and secularists, may have dominated political life in France, a common denominator for human dreams and aspirations could be found in scientific knowledge. While this may have been repeatedly unmasked as an illusion in the years since then, the appropriation of the Foucault pendulum as a political symbol persisted well into the twentieth century, and not just in France. In Soviet Leningrad, it formed the centerpiece of a museum installation that combined atheism, materialism, and Bolshevism; in Washington, DC, it was called on to reconcile national history with universalism. The pendulum thus also oscillated between Communism and capitalism. And in the lobby to the United Nations Headquarters in New York, diplomats ceremoniously file past the pendulum on their way to the General Assembly Hall, as if guided in their decision-making by the inexorably rotating earth and solemnly swinging pendulum. To be sure, such striking examples could not be multiplied at will, yet they attest to the fact that Foucault's pendulum is *also* an object of political iconography—due to the sites where it has been installed, the calculated ways in which it has been staged for mass consumption, and the numerous images made of it and circulated around the world.

Aesthetic: when Foucault conducted his first experiments in a private basement and repeated them soon after in the Meridian Room of the Paris Observatory, he could only imagine their effect on the broader public. The decision to move the pendulum to the Panthéon was politically motivated, but when it finally occurred, something else became clear. Foucault himself was the first to point out the rapt attention spectators paid to the phenomenon once they had become attuned to it. For this they needed patience, time, and focus—much as they would when contemplating a painting in an art gallery. The pendulum was not a painting, of course, but its slowly and steadily oscillating sphere, suspended from the ceiling by a long cable, evidently conveyed a sense of dignity and repose that stood in stark contrast to the increasingly hectic pace of urban life in the French capital, as well as the dizzying speed with which the earth seemed to spin on its axis and hurtle through the cosmos. Physics alone could not account for this special feeling in the observer, nor could the length of the cable, which is solely responsible for the pendulum's period of oscillation. The decision to use a gleaming polished sphere, rather than some other geometrical shape, may have prompted some spectators to think of a miniature model of the earth floating serenely through space.

And finally, the mise-en-scène also played a part. The display in the Panthéon, with a circular oscillation plane from which spectators were separated by a balustrade, served as a model for many more of its kind, although quite different formats were chosen, as well. The twentieth century saw further spectacular demonstrations, ranging from the Constructivist installation in the early Soviet Union and the floating installation in UN Headquarters to Hollywood dreamscapes. As we will see, it is impossible to draw a clear distinction between political and aesthetic connotations in all these public stagings of the pendulum. They all take up the question of the human observer in some way or other.

Since the summer of 2018, finally, a pendulum installed by artist Gerhard Richter in the Dominican Church in Münster has opened an additional perspective on the fraught relationship between cosmic processes and human concerns. From Foucault to Richter—this may seem an unlikely pairing, for what kind of trajectory connects the two? From faith to science, or from science to art? Although not entirely incorrect, this is far too inexact. No one needs convincing today that the earth spins on its axis. Yet the fact that churches, the incubators of faith, have provided the setting for the pendulum experiment from the beginning is far from trivial. It gave rise to problems at the Panthéon, and Richter's project, too, met with criticism from some Catholic theologians even before the work's official opening. Beyond the varying historical circumstances, this prompts us to ask: Which spaces come into consideration for which scientific experiments? How are they both transformed in the process? Above all, what does such a constellation entail for how the pendulum is perceived? Clearly, a Foucault pendulum displayed in a consecrated or deconsecrated church is both the same as *and* different from one hanging in a technology museum. They involve different viewpoints, different associations, different connections in the mind and the senses — all of which brings us back to the observer. Who is doing the seeing here? What do they see when they see?

These questions occupy the border zone between science and art because they reveal an anthropological dimension to the Foucault pendulum that — as I have already indicated — directly concerns the relationship between seeing and understanding. The experiment demonstrates the earth's rotation, temporarily shrouding the mathematical complexity of the processes it illustrates. An installation of simplicity and elegance, beauty and regularity, it provides, for a few moments of sustained attention, sensuous access to a movement that ordinarily escapes detection by the senses; it makes the imperceptible perceptible. There still remains an epistemic gap for those who lack the relevant expertise in mathematics and physics, yet this gap is plugged by the almost minimalist simplicity of the experiment. To that extent, while the pendulum satisfies a longing for visual evidence, it simultaneously irritates a perspective accustomed to a hand and dial and poses questions about the relationship between historical and cosmic time.

Even the universe and the earth have a history, and planetary rotations self-evidently occur in time. The process disclosed by Foucault's pendulum, however, is cyclical and apparently unchanging. This difference in temporal orders may be inferred from two contrasting semantics of the pendulum. The pendulum of the grandfather clock, which represents the passing of time and hence the transience of life, stands opposed to Foucault's pendulum, which symbolizes a suspension or supersession of time. Transcending temporal limitations, it seems to grant a glimpse into the abyss separating the cosmic order from the realm of human affairs. Unlike the telescope, which preserves the universe in its unfathomable remoteness, the pendulum brings distance up close. For the brief spell in which we contemplate the experiment, it is there right before our eyes. For that reason, the history of the Foucault pendulum entails more than a victory of reason over faith or science over religion. Scientific rationality is seasoned with a pinch of revelation, however this may be interpreted. As I hope to show in what follows, this ambiguity accounts for the pendulum's ongoing power to fascinate, disconcert, and inspire those who fall under its sway.

CHAPTER ONE

The Long Path to the Periphery

Ptolemy and the Postulate of Visibility

The confrontation between cosmological model and orienting worldview was never more painful than in the seventeenth century, when the pact between Greek cosmology and biblical wisdom broke down within a few brief decades. Sanctioned by the authority of the church, geocentrism could find support in Joshua 10:12–13, which reports how God commanded the sun to stand still: "The sun stopped in the middle of the day and delayed going down about a full day." That day, Joshua adds, was like no other, before or since. This can mean only that the sun ordinarily moved.

Astronomical geocentrism drew on the authority of Claudius Ptolemy, whose book *Almagest* (or *Mathematike syntaxis*) remained virtually unchallenged until Copernicus. There was no scholarly consensus on the earth's position in relation to the sun, however. Aristotle dedicated an entire book to the heavens, discussing the earth's mobility or immobility in a way that suggested both views had their proponents at the time. The geocentric system aligned with the Aristotelian theory of movement, which maintained that each body has a natural motion that strives toward a specific goal. A heavy body such as the earth falls toward the center of the cosmos and comes to rest upon arriving there, whereas light and fiery bodies ascend from the center to the outer rim, where they wheel eternally around the center. According to the philosophical theory of the four elements (fire, water, air, earth), the earth was associated with heaviness and the sun with light. Yet Aristotle did not rest content with this cosmological explanation, backing it up with an empirical argument for geocentrism that would prevail for centuries to come: if an object is thrown straight up into the air, it always falls back to the same spot, and this would be impossible if the earth were in constant motion.[1]

Another indisputable phenomenon was the alternation of night and day and the periodicity of the year with its seasons. This admitted a heliocentric explanation, as well as a geocentric one. In the absence of surviving documentation, we do not know how Aristarchus of Samos, who lived after Aristotle, supported this position.[2] Whatever his arguments may have been, they failed to catch on. On the other hand, Ptolemy built up the case for geocentrism. If the earth were rotating at great speed on its own axis from west to east, how could clouds cross the sky from west to east? Given that they would invariably be overtaken by the earth, clouds should always drift to the west, which was clearly not the case. Combined with Aristotle's point that an object thrown vertically in the air should land farther to the west due to the earth's rotation — for which there was no empirical evidence — Ptolemy had plausible, seemingly irrefutable arguments on his side that were confirmed by direct observation.[3] Hans Blumenberg summed up this optical ancien régime: "The traditional concept of nature was associated with a kind of *postulate of visibility* that corresponded both to the finite extension of the universe and to the idea that it had its center and purpose in humankind."[4] The strength of geocentrism lay in this link between what could be intuited with the senses and what made intuitive sense.

More than fourteen hundred years separate Ptolemy and Copernicus. Throughout this long period, the earth's fixed position at the center of the universe was never seriously called into question — not in late antiquity, not in the golden age of Arabic science from the eighth to twelfth centuries, and certainly not in the Christian

Middle Ages. References to the earth's rotation were confined to ephemeral thought experiments and counterfactual speculations that had no real consequences. The Persian polymath al-Biruni is a case in point. He had a wealth of mathematical, physical, and astronomical information at his fingertips and challenged Aristotle's stone-throwing argument with a clever thought experiment. Al-Biruni recounted the musings of an unnamed astronomer. Assuming a rotating earth, what if *two* movements have to be accounted for when a stone is thrown straight up in the air: the universally visible vertical movement as it rises and falls, but also a second, horizontal movement, concealed from the observer, occurring at exactly the same speed from west to east as the earth?[5] Taken together, these two movements would ensure that the stone did not drift westward, but maintained its seemingly vertical descent. Arguments for geocentrism might have been challenged in a discursive space cleared of conventions, appearances, traditions, and values, but al-Biruni had no interest in privileging abstract reason over sensory perception in this way. He closed his thought experiment with the statement: "Yet none of this exists, and the earth does not rotate on its place about its axis."[6]

Al-Biruni's ingenious little thought experiment did not refute Ptolemy, nor did it anticipate the law of inertia theorized by Galileo, Descartes, and Newton. The writings of al-Biruni were ignored by European scientists until long after the Copernican turn and played no role in further discussions. Even in the Arab scientific culture that predated the ascendance of natural-philosophical discourse in the Christian Middle Ages, geocentrism was never seriously called into question. As such, it makes little sense to characterize the persistence of the Ptolemaic worldview until the advent of Copernicanism as a triumph of Christian faith over superior knowledge. Geocentrism maintained its hold because it satisfied epistemic, metaphysical, and practical needs alike. Islamic astronomers were well aware of the inconsistencies and idiosyncrasies that bedeviled Ptolemaic cosmology, which they sought to mitigate through a series of complicated additional assumptions.[7] Meanwhile, theologians argued that God's infinite wisdom could not fully be grasped by the human mind.

Copernicus before Copernicanism

In recent scholarship, Nicolaus Copernicus is presented less as a revolutionary than as a conscientious, somewhat conservative astronomer who set out to correct the ancients and offer fresh hypotheses without meaning to usher in a new worldview.[8] In 1797, his early biographer, the physicist and philosopher Georg Christoph Lichtenberg, had already noted a tension between the cautious reformer and the founder of a new astronomy. On the one hand, Copernicus did not "reject the Ptolemaic system outright, he merely stated that it had faults like all the rest, which were also old; none completely satisfied the phenomena, and each contravened its own principles." On the other hand, Lichtenberg writes, progress in astronomy could not be made until the coming of "the man who commanded the sun to stand still."[9] The difference between these two characterizations stems from the fact that one is based on Copernicus's own statements, the other on the impact his teachings had on astronomy (with a few decades' delay).[10]

For all its shortcomings, the Ptolemaic system had no serious rivals around 1500. The question of how Copernicus came to initiate its demise has long puzzled historians of astronomy and has yet to be fully resolved. Where did Copernicus find his models? A work by the Königsberg mathematician, Johannes Müller (= Regiomontanus), was long taken to be his most important reference point, but observations and models of the Arab astronomer Ibn-al-Shatir have recently emerged as the key inspiration for his short treatise *De hypothesibus motuum coelestium a se constitutis commentariolus*, which circulated among scholars in manuscript beginning around 1510.[11] Should this theory be confirmed, the history of heliocentric cosmology would undergo a moderate transcultural expansion without this detracting from the achievement of the church canon from Frauenburg.

In this treatise, Copernicus presented his initial proposals for rectifying Ptolemy's defects, although it is unclear whether he had full confidence in his own findings at the time. It is telling that he decided not to commit the *Commentariolus* to print. Perhaps he was put off by the need to posit an immobile sun at the center of the universe and a moving earth to support the observations and calculations with which he corrected Ptolemy.[12] This would mean that the assumption of a heliocentric model did not follow inductively from his new observations. On the contrary, for Copernicus, his findings made most sense if he took the earth's motion to be axiomatic. This was still far removed from anything resembling a proof. Reactions to the manuscript were accordingly muted.

Preoccupied with his church duties in Frauenburg and other activities and untroubled by any pressure to publish, Copernicus spent decades developing and refining his hypotheses. Toward the end of his life, he found an ally in the young Protestant, Georg Joachim Rheticus, recently appointed to the University of Wittenberg. Rheticus even came to Frauenburg, promising Copernicus that he would arrange for his book to be published in Nuremberg—a task he then delegated to the Lutheran Andreas Osiander. This decision had momentous consequences. Unlike Copernicus and Rheticus, who had ample time to familiarize themselves with the possibility of heliocentrism, Osiander recognized the explosive implications of the new model for the old worldview. Clearly reluctant to challenge the authority of Holy Scripture, he added a dialectical foreword to the book, approved by neither Rheticus nor Copernicus, in which he insisted that the literal truth of the sun's immobility did not need to be accepted for the astronomical observations and calculations contained in the following pages to be regarded as legitimate and useful. Osiander presented the hypotheses as *fundamenta calculi* (bases for calculations), not as *articuli fidei* (articles of faith), as he had previously written in a letter to Copernicus.[13]

The opposition to Copernicus voiced by the Reformation leaders Martin Luther and Philipp Melanchthon has often been cited in the context of downplaying the achievements of *De revolutionibus*. Melanchthon did indeed criticize heliocentrism,[14] while Luther allegedly railed against the new system before his tablemates in 1539: "The fool [that is, Copernicus] wants to turn the whole art of astronomy upside-down. However, as Holy Scripture tells us, so did Joshua bid the sun to stand still and not the earth."[15] We can now appreciate the wit of the previously quoted passage from Lichtenberg, who smuggles his subversive metaphor into the proverbial setting of the Old Testament, replaces God with Copernicus, and even takes a swipe at those who invoked the Book of Joshua against heliocentrism. In the sixteenth century, the literal authority of Holy Scripture was still taken for granted from Rome to Wittenberg, but it afforded room for interpretation, especially in Wittenberg.[16]

Luther's fidelity to the Bible should not lead us to place undue emphasis on his tirade against Copernicus. Even the report that he called the astronomer a "fool" may be apocryphal; the term is missing from a different transcription made of the same speech.[17] Nowhere else in his work did Luther express his views on Copernicus, suggesting that this cosmological question was of no great concern to him.[18] At any rate, Luther could not have been against the Copernican system, if for no other reason than that it did not yet exist in his lifetime.

When *De revolutionibus orbium coelestium* finally appeared in 1543, it did not yet herald a "Copernican revolution." Prefaced with Osiander's interpretive guidelines, which left divine truth untouched, the book was perceived as a threat neither in Rome nor in Wittenberg. Copernicus's measured style of thinking and writing helped allay possible concerns. He held fast to central ancient ideas such as circular planetary orbits, and he repeatedly presented the earth's rotation as an exception that could provide a simpler explanation for the behavior of the celestial spheres. He had taken the liberty, he wrote, "to reflect on the earth's motion" and made his interpretations "on the assumption of some motion of the earth."[19] Copernicus chose his words carefully. He wrote of "some motion," understanding that two movements were involved: the diurnal rotation of the earth on its own axis and its continuous movement through the cosmos.[20] This called into question the prevailing view that the earth occupies the midpoint of the universe. But he never claimed to have *demonstrated* the earth's movement. This he could not do, as he acknowledged and justified with an interesting argument: "It is the earth, however, from which the celestial ballet is beheld in its repeated performances before our eyes." Astronomical evidence was tied to a particular viewpoint. Incapable of taking flight, human observers could not transcend their earthbound perspective: "Therefore, if any motion were to be ascribed to the earth, in all things outside it the same motion would appear, but in the opposite direction, as though they were moving past it. . . . However, if you were to grant that the heavens had no part in this motion but that the earth rotated from west to east, upon earnest consideration you would find that this was the actual situation concerning the apparent rising and setting of the sun, moon, stars, and planets."[21]

If we read this sentence as a thought experiment, disregarding for a moment its weighty philosophical implications, its cautious use of the subjunctive becomes understandable. For it was inconceivable at the time that a human being could ever set foot on another planet and observe the earth from there. Copernicus broke with the tradition that contented itself with gazing at the heavens and waxing lyrical about God's wisdom, further increasing the complexity of the Ptolemaic model through the need for cumbersome additional assumptions to account for the movements of the celestial machinery. This break came at a considerable epistemological cost. Copernicus did not purport to have seen and demonstrated the dual motion of the earth. Instead, he initially appealed to tradition by recalling that the earth's rotation on its own axis had already been posited in antiquity. His insistence that he was not the first to make such a grand claim was a form of insurance in an era that frowned on radical originality. Yet Copernicus also had to make clear that he was not simply parroting ancient authors whose views had long been superseded by Ptolemy. That is why he specifically pointed out that based on his observations and calculations, he had arrived at new arguments capable of standing up to scholarly scrutiny.[22]

Copernicus assumed that his theory would attract commentary from outside the ranks of the fledgling scientific community. Whether or not he was aware of Luther's polemical table talk, the preface to *De revolutionibus* reveals that critical remarks from both Catholic and Protestant leaders had not escaped his attention. If "babblers . . . claim to be judges of astronomy, although completely ignorant of the subject and, badly distorting some passage of Scripture to their purpose, will dare to find fault with my undertaking and censure it: I disregard them even to the extent of despising their criticism as unfounded."[23] This could be taken to mean that Copernicus did not consider the passage Luther cited from the book of Joshua to be a reliable statement about the behavior of the sun. The Catholic canon had no pressing reason to defend himself against Protestantism, but Rome was another matter. The sentence attacking the "babblers" was addressed primarily to Pope Paul III, the book's dedicatee.

Lichtenberg coined a lovely phrase to describe this dedication: "The clever canon stuck to the rule: the safest place for the fly is on the flyswatter."[24] If he wanted to recruit the pope as an ally, in other words, Copernicus had to avoid appearing to challenge ecclesiastical authority with an all-encompassing truth claim. At the same time, however, he granted a privileged status to the mathematician's expertise. Although the cosmic order is understandable, it can be understood only by being investigated. Until then, it is better not to say anything. This distinction was a first, rhetorical step toward a truly scientific astronomy, a faint foretaste of Galileo's clear-eyed, disillusioning statement a century later that only a select few are qualified to read in the book of nature and comprehend the mathematical language in which it is written.[25]

Even at this early stage on the journey to an abstract, mathematical explanation for cosmic phenomena, Copernicus already privileged rational calculation over sensory perception when accounting for the movements of the heavenly spheres. Nietzsche was a scrupulous reader. A rotating earth may not have been senseless, but until Foucault's pendulum, it defied the senses, and this provoked resistance. Copernicus was spared the ferocious scrutiny of the Inquisition because he had spoken of a hypothesis, not an irrefutable truth. A case could be made that he had set out to provoke discussion among scholars, not plunge the Christian world into turmoil.[26] In the first decades after Copernicus's death, neither of these things happened. With Arthur Koestler, one could even say that *De revolutionibus* was "the book that nobody read" in the second half of the sixteenth century.[27] Yet in the end, astronomical and theological discussions proved inseparable, as would be revealed over the course of the debates that eventually saw *De revolutionibus* placed on the Index of Forbidden Books and Galileo Galilei turned into an iconic martyr in the fight against Catholic dogma.

Cosmic Harmony, or, Feeling Equal to the Whole Sky

How did one become a Copernican in the sixteenth century? How did one go from making practical use of the canon's astronomical observations and calculations to embracing (or repudiating) its cosmological consequences? What role was played in all this by the dual movements of the earth? And how did the visual evidence relate to rational calculation? These are big questions that can be pursued with reference to the substantial research literature,[28] although I will generally limit myself to aspects relevant to the question of the earth's daily rotation on its axis. No attempt will be made here to survey the history of the genesis and gradual acceptance of the Copernican worldview.

Before 1600, there were only a handful of avowed Copernicans in the scholarly community.[29] The most significant were Johannes Kepler and Galileo Galilei. Their very different contributions paved the way for the breakthrough of heliocentrism—one with physical arguments that culminated in the laws that took his name, the other by turning the recently invented telescope to the skies and making a series of astronomical discoveries that, properly explained, would dispel lingering doubts about heliocentrism. Their two seminal works, Kepler's *Astronomia nova* and Galileo's *Siderius nuncius*, appeared in swift succession in 1609 and 1610, respectively, marking these two years as *anni mirabiles* in the history of scientific publications.

Kepler was all but unknown in the European republic of scholars when he published his first work, *Mysterium cosmographicum*, in 1596. He reported there how he had been converted to Copernicanism during his studies in Tübingen.[30] In Kepler's view, it made no sense to accuse Copernicus of having drawn the right conclusions from the wrong premises. Directed against the interpretation put forward by Osiander, this argument ushered in a new phase in the reception of Copernicus in which cosmological considerations overshadowed all others. What spoke for the heliocentric model was its simplicity and its agreement with a range of celestial phenomena. Kepler used a rhetorical question to advance the notion of a rotating earth, inviting readers to decide "whether it is easier for it to happen and to be believed that that small point within the little circle A, and hence the earth, rotate in one direction, or that the complete universe goes . . . with inconceivable rapidity, and is subject to nothing but that small point, which alone is motionless, because there is nothing outside?"[31] Interestingly, two thoughts coincided here: an economic perspective, according to which nature acts with the utmost parsimony, and the earth's demotion to a planetary speck occupying its God-given place in an unfathomably vast universe. Goethe once said of Tycho Brahe that he "felt equal to the whole sky."[32] Much the same could be said of Kepler, who felt equal to a universe where God reveals himself in a cosmic harmony disclosed through mathematical means.

Following the publication of *Mysterium cosmographicum*, Kepler began searching for allies. He sent copies of the book to Europe's most famous living astronomer, Brahe himself, and to Galileo, whose reputation as a brilliant physicist had spread north of the Alps. This attempt to forge a circle of like-minded scholars stands at the beginning of a chain of scientific and political events that would end with Copernicanism being at once condemned by the church and largely accepted by the scientific community. Brahe studied Copernicus intensively but never became a convert. He instead developed a geoheliocentric model in which the sun and moon circled the earth, while all the other planets orbited the sun. He nonetheless invited Kepler to work with him in Prague, where he served as court mathematician for Holy Roman Emperor Rudolf II. This proved crucial for Kepler's development. After Brahe's death in 1601, he could use the detailed observational data his mentor had amassed over many decades, especially concerning the orbit of Mars, as the basis for his own calculations.

Having perused Kepler's first work, Galileo dashed off a letter of thanks that contained two extraordinary admissions: first, that he had been convinced of the truth of heliocentrism for years, and second, that he had no current intention of publishing anything on the topic for fear that he would be subjected to the same ridicule as Copernicus.[33] Whatever circumstances led Galileo to embrace heliocentrism, at this stage, in 1597, he seems to have been more concerned for his reputation than scared of the instruments of the Inquisition. His fame to date had rested on a new, anti-Aristotelian theory of motion. This was spectacular stuff, but it did not contribute much to the Copernican cause. Kepler's letter in reply, urging Galileo to press ahead with the truth, acknowledged that he already knew what it was like not to be taken seriously: "It is not only your Italians who cannot believe that they move if they do not feel it, but we in Germany also do not exactly endear ourselves with this idea. Yet we have rational arguments on our side to arm ourselves against these difficulties."[34] These sentences express an opposition between perception and truth that bids farewell to the postulate of visibility, as well as outlining the problems that would emerge in its wake.

The patterns of behavior that made life difficult for Kepler and Galileo have repeatedly been observed in the history of the arts and sciences. New theories, whether heliocentrism, the theory of evolution, or relativity, or new artistic movements, whether impressionism or twelve-tone music, are initially met with silence or ridicule before being perceived as a real threat to the status quo and subjected to sustained assault. As is well known, Copernicanism was not spared this fate. Yet it would be too simple to set up an opposition between unprejudiced scientists guided solely by the light of truth and orthodox priests interested only in preserving their power. For all the revolutionary force of its ideas and observations, heliocentric astronomy faced a series of problems that the proponents of the new doctrine could not easily resolve.[35] In the first decades of the seventeenth century, no single Copernican had embraced all the available arguments for the new theory and adequately acknowledged every plausible objection to it. While Kepler and Galileo went to great lengths to find new arguments for their convictions, their checks were not always covered, epistemologically speaking.

No one made this point more trenchantly than Paul Feyerabend. In *Against Method*, he described Galileo as a master in the art of "propaganda" and "psychological tricks."[36] This was not as disrespectful as it sounds; Feyerabend made clear that Galileo had excellent reasons for his arguments. Yet while Nietzsche had characterized Copernicus as having triumphed over optical evidence, for Feyerabend, Galileo was by far the more persuasive writer. Once again, the shift from the primacy of perception to reason forms the sore spot. Both Kepler and Galileo were aware of this, although each dealt with it in different ways.

Problems with his eyes meant that unlike Brahe, Kepler was not a passionate stargazer. Still, he never questioned the importance of observation; hence his keen interest in Brahe's trove of astronomical data. Kepler was looking for opportunities to close the gap between perception and reason. He proposed to come up with a theory where "the calculation matches the accuracy of sense perception."[37] This degree of precision in mathematical calculation, which Kepler went on to demonstrate to impressive effect, would have to make up for deficiencies of perception at other points in the Copernican system. The fact that he could not directly observe the earth's movement did not seem to trouble him. Otherwise, he would hardly have ignored the observational gap bound up with the earth's rotation. What Kepler offered, in short, was a theoretically motivated departure from the primacy of perception, a departure made easier to bear through accuracy being declared a divine attribute. Mathematics was trustworthy not because it was a human contrivance but because it represented the language in which God had written the book of nature. The ability to read in this book could no longer rely solely on the senses. This did not diminish the role played by the senses in granting access to it. Observation was still essential, and the more new, previously unknown facts were discovered, the better. However, some early seventeenth-century naturalists were convinced that these observations had to accord with the language in which the book lay open before us. This language revealed itself to mathematically trained reason.[38]

The development of the fundamental laws for heliocentrism can be understood against the background of this philosophical perspective. In brief, they state the following:[39]

1. Planets move in elliptical orbits around the sun, with the sun at one of the foci, not in circles.
2. The rate at which a planet sweeps over equal areas in its elliptical orbit during equal intervals of time is constant. This means that a planet accelerates as it approaches the sun and decelerates as it moves away from it.
3. The square of the orbital period—the time it takes for a planet to complete one orbit around the sun—is directly proportional to the cube of the semimajor axis of its elliptical orbit (its average distance from the sun).[40]

What distinguished these laws from earlier ideas about cosmic processes — including those of Copernicus — becomes clearer once we recall that Kepler attributes the planets' elliptical orbits and their respective speeds, which vary according to their distance from the sun, to the force of attraction exerted by the sun over the planets. This was a revolutionary insight, and it has often been pointed out that Kepler was on the brink of formulating the law of gravitation discovered by Newton some seventy years later. Certainly, no one before Kepler had postulated quasi-magnetic solar forces as causative factors for planetary movements while also indicating the mathematical laws that govern these movements. Yet Kepler's concept of force was quite different from the one that led Newton to the law of gravitation. Where for Newton, gravity was a universal physical power with causes unknown, for Kepler, the forces emanating from the sun were the expression of an animated cosmos.

The metaphors I have used to characterize Kepler's approach — the book of nature, the language of mathematics — aim to highlight similarities with that other great Copernican, Galileo. However, such metaphors also obscure the fundamental differences between them. In his late astronomical work, *Harmonices mundi*, Kepler devoted an entire chapter to music, drawing an analogy between musical harmonies and the movement of the spheres. This obvious reference to the Pythagorean link between music and mathematics lends itself to a different metaphor from that of the heavens as a book: the cosmos as the great orchestra performing God's compositions, which can be grasped both musically and mathematically. For Kepler, this orchestra is an active, animated organism, its harmonious order an expression of the beauty and perfection that correspond to the purpose of existence itself.[41]

The idea of an animated universe and the planets as living beings stands in stark contrast to an understanding of nature as a passive structure ruled by mechanical forces. Kepler cannot be said to have contributed to the much-invoked mechanization of the seventeenth-century worldview. This mechanistic and rationalist tradition, primarily established by Galileo, Newton, René Descartes, and Robert Boyle, would prove to be constitutive for the modern natural sciences, but it had little time for Kepler's philosophy of nature. This is why Kepler, despite his pathbreaking contributions, has sometimes been seen as an eccentric figure among the architects of the Copernican worldview — unfairly so, since in the early seventeenth century it was still unclear whether cosmology would evolve in the direction of a harmonious or mechanical universe. Kepler's outsider status is less interesting here than the fact that early Copernicanism was a composite of quite diverse philosophical assumptions and convictions.

Not All Copernicans Are Alike

As pointed out in the Introduction, Galileo likewise believed that the book of nature was written in the language of mathematics. Yet his first major contribution to the new cosmology, the *Sidereus nuncius*, latched onto the very point that Kepler had just relativized through mathematical proof: observation. Theoretically, peering through the miraculous new instrument, the telescope, could have been eminently compatible with deriving the law-governed behavior of planetary movements. Yet history does not always unfold in such a way that the connections between scientific insights are immediately grasped by all the key players. Galileo never officially acknowledged Kepler's laws in his own lifetime. As protagonists of a precarious minority position, Kepler and Galileo might have been expected to draw gratefully on whatever further arguments for Copernicanism were made available to them, yet such was clearly not the case. Kepler greeted the *Siderius nuncius* with ecstatic approval. So why did Galileo not reciprocate?[42] One plausible interpretation of this asymmetry goes back to art historian Erwin Panofsky, who described a fundamental difference between Galileo and Kepler. Whereas the former was convinced that rectilinear movement was the dominant principle of movement in the physical world, the latter was committed to the perfection of the circle, an idea rooted in pre-Socratic natural philosophy and entrenched in both the Platonic and Aristotelian traditions. Galileo made no distinction between mathematical, mechanical, and aesthetic preferences, as Panofsky convincingly demonstrated with reference to his remarks on art, anatomy, physics, and astronomy. For Galileo, the beauty of circular movement entails its uniformity. His mind was thus closed to both elliptical planetary orbits and the idea that a planet's speed could vary based on its distance from the sun.[43]

Kepler bypassed a problem with observation; Galileo ignored a model for the celestial spheres. Rather than describing these behaviors as "psychological tricks," suggesting that the available facts were willfully distorted to fit a predetermined (mis)interpretation, they should perhaps instead be put down to neglect. In Ludwik Fleck's sociology of knowledge, this involved ignoring certain phenomena that are incompatible with one's own thought style. Fleck defined a thought style as a propensity for "directed perception, with corresponding mental and objective assimilation of what has been so perceived. . . . It is characterized by common features in the problems of interest to a thought collective, by the judgments which it regards as evidence, and by the methods which it applies as a means of cognition."[44] Scientists perceive what fits into their conceptual framework. The unobservability of the earth's rotation was a strong argument against Copernicanism at the time, which is why Kepler set this problem aside while Galileo addressed it head-on. Elliptical orbits clashed with the preference for circles rooted in Greek natural philosophy, hence Galileo's lack of interest in them. Around 1600, individuals with vastly differing scientific and philosophical positions thus embraced Copernicanism. In Fleck's terms, this implied that a science-based worldview can accommodate a wide range of thought styles.

Few events in the history of science have been scrutinized as closely as Galileo's role in advancing Copernicanism, both in relation to scientific and philosophical questions and in artistic and literary contexts.[45] His engagement in the Copernican cause began with the statements cited above from his early letter to Kepler and continued with astronomical discoveries such as lunar craters, the moons of Jupiter, sunspots, and the phases of Venus, which brought the physicist great renown but also reproof from the Inquisition due to the uncompromisingly heliocentric spin he put on these phenomena. The climax came in 1632 with the publication of the *Dialogue Concerning the Two Chief World Systems*, which led to charges and condemnation from the Inquisition that saw the elderly Galileo confined to his Tuscan country house for the rest of his life.

If Galileo had been reluctant to risk derision by prematurely declaring his allegiance to Copernicus, as he informed Kepler, he probably would have remained silent even longer had he not become an early adopter of the Dutch invention of the telescope. After that, everything happened in a rush. According to his first biographer, Vicenzo Viviani, news of the invention reached his ears in April or May 1609. By March 1610, he had already committed *Sidereus nuncius* to print,[46] a hastily written treatise summarizing his eagerly anticipated findings in favor of heliocentrism: the irregularities and unevenness of the lunar surface and the four moons that orbit Jupiter much like the moon orbits the earth.[47] As if these spectacular revelations were not enough, Galileo promptly announced another, longer work on the construction of the universe that would dispel all remaining doubts: "For we will demonstrate that she [the earth] is movable . . . and we will confirm this with innumerable arguments from nature."[48]

With that, Galileo at least implicitly admitted that he had not yet clinched his case. Carried away by the excitement of his astronomical discoveries, he could not possibly know whether he would ever be able to deliver the proof he had just so emphatically pledged. The "innumerable arguments," meanwhile, show Galileo as a skilled rhetorician and shrewd self-promoter. He was presenting himself as a convinced Copernican who had rejected both geocentrism and Brahe's Ptolemaic-Copernican compromise model, still a plausible alternative at the time. He even went a step further by deliberately attacking the position that would tolerate heliocentrism only

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