THE COPERNICAN REVOLUTION
IN ASTRONOMY

Before we try to explore the broad impact of Copernican astronomy on early modern culture, a very short discussion of traditional astronomy and of Copernicus’ reform of astronomical theory is necessary. Within the medieval and early Renaissance university, astronomy was taught as a branch of mathematics and was usually formally divorced from natural philosophy. Though there were exceptions, astronomers usually accepted the limits of their domain as they had been articulated in Simplicius’ commentary on Aristotle’s *Physics* in antiquity.

It is the business of physical inquiry to consider the substance of the heaven and the stars, their force and quality, their coming into being and their destruction, nay, it is in a position even to prove the facts about their size, shape, and arrangement; astronomy, on the other hand, does not attempt to speak of anything of this kind, but proves the arrangement of the heavenly bodies by considerations based on the view that the heaven is a real cosmos, and further, it tells us of the shapes and sizes and distances of the earth, sun, and moon, and of eclipses and conjunctions of the stars, as well as of the quality and extent of their movements. Accordingly, as it is connected with the investigation of quantity, size, and quality of form or shape, it naturally stood in need, in this way, of arithmetic and geometry. The things, then, of which alone astronomy claims to give an account it is able to establish by means of arithmetic and geometry. Now in many cases the astronomer and the physicist will propose to prove the same point, e.g., that the sun is of great size or that the earth is spherical, but they will not proceed by the same road. The physicist will prove each fact by considerations of essence or substance, of force, or its being better that things should be as they are, or of coming into being and change; the astronomer will prove them by the properties of figures or magnitudes, or by the amount of movement and the time that is appropriate to it. Again, the physicist will in many cases reach the cause by looking to creative force; but the astronomer, when he proves facts from external conditions, is not qualified to judge of the cause, as when, for instance, he declares the earth or the stars to be spherical; sometimes he does not even desire to ascertain the cause, as when he discourses about an eclipse; at other times he infers by way of hypothesis, and states certain expedients by the assumption of which the phenomena will be saved. For example, why do the sun, the moon, and the planets appear to move irregularly? We may answer that, if we assume that their orbits are eccentric circles or that the stars describe an epicycle, their apparent irregularity will be saved; and it will be necessary to go further and examine in how many different ways it is possible for these phenomena to be brought about, so that we may bring our theory concerning the planets into agreement with that explanation of the causes which follows an admissable method. Hence we actually find a certain person, Heraclides of Pontus, coming forward and saying that, even on the assumption that the earth moves in a certain way, while the sun is in a certain way at rest, the apparent irregularity with reference to the sun can be saved. For it is no part of the business of an astronomer to know what is by nature suited to a position of rest, and what sort of bodies are apt to move, but he introduces hypotheses under which some bodies remain fixed, while others move, and then considers to which hypotheses the phenomena actually observed in the heaven will correspond. But he must go to the physicist for his first principles, namely, that the movements of the stars are simple, uniform, and ordered, and by means of these principles he will then prove that the rhythmic motion of all alike is in circles, some being turned in parallel circles, others in oblique circles.

This statement makes it very clear that, although astronomy was grounded in a few very general principles taken from natural philosophy, astronomical systems did not usually claim to address the “causes” of celestial motions. In this sense, late medieval astronomy was peculiarly well situated to be the beneficiary of nominalist attitudes toward knowledge, and did not have to be reformulated in any significant way in response to Ockhamist ideas. Its function was to produce hypotheses that could save the appearances without claiming anything about the reality underlying the appearances.

By the early sixteenth century almost all European astronomical calculating systems were variants on the scheme developed by Claudius Ptolemy and presented in the work that had been titled the *Almagest* (Great Book) by its Islamic translators and commentators. Ptolemaic astronomy was reintroduced into European scholarship by Georg Purbach (1423–1461) in his *New Theory of the Planets.* And Purbach’s student, Regiomontanus (1436–1476), published an *Epitome of Ptolemy’s Almagest,* which summarized its mathematical parts.

The Ptolemaic system of astronomy is geocentric (earth centered), and assumes that the solar year (the period from summer solstice to summer solstice, or from longest summer day to longest summer day) is constant. The system had initially been designed to account for such phenomena as the variable sizes of such bodies as the moon, Venus, Mars, and Mercury; the daily motion of the general framework of the so-called “fixed” stars; the differing periods of motion of the planets through the background of the fixed stars; and
the variability of angular velocity of the planets within each cycle—a variability that was so great that the planets not only appeared to slow down and speed up, but even appeared to stop and back up (have retrograde motion) occasionally.

In order to account for such phenomena, Ptolemy employed a number of mathematical devices that call for some explanation. We begin by thinking that the simplest possible heavenly motion would be a constant angular motion in a circle centered on the earth. Suppose for a moment that \( S_1, S_2, S_3, \) and \( S_4 \) in figure 21 are fixed stars 90° from one another on the "sphere of the fixed stars." Suppose also that the rotational speed of the sphere of the fixed stars is constant. If Planet \( P \) moves with constant angular velocity on its circle centered on \( E \) it will take equal times to move from \( S_1 \) to \( S_2 \), from \( S_3 \) to \( S_4 \), from \( S_1 \) to \( S_4 \), and from \( S_3 \) to \( S_1 \), again, as viewed from \( E \) against the starry background. Furthermore, it will take the same period to move from \( S_1 \) around its circle and back to \( S_1 \) in successive revolutions—that is, its period of revolution will be constant. Lamentably, no heavenly body moves so simply; but the sun moves in such a way that a very

![FIG. 21. Simplest possible model of a planetary orbit (\( \alpha = kl \)).](image)

![FIG. 22. Eccentric circle model for Sun's motion.](image)
If we assume that the sun moves with a constant angular velocity about the point C, which is displaced from the center of the earth as shown, then we can account for all of the observed phenomena. The circular path assumed for the sun is called an eccentric circle and the ratio of the distance EC to the radius R of the circle is called the eccentricity of such a circle.

Mathematicians after Hipparchus showed that an eccentric circle could be reproduced by another mathematical device, which was to have great importance for Ptolemaic astronomy. Consider figure 23. We begin with a circle centered on the earth (the deferent). On this circle the center, C, of another circle (the epicycle) moves with a constant angular velocity \( \alpha \). While C moves along the deferent, the point P, representing the sun, revolves along the epicycle with an angular velocity of \(-\alpha\). In this way the point representing the sun traces out a path identical to the eccentric circle of figure 22.

Now, if all we could do with deferents and epicycles was to reproduce eccentric circles, their use would be totally uninteresting. But consider figures 24 and 25, in which the angular motions of the point P about the center of the epicycle C are respectively \(-2\alpha\) and \(8\alpha\).

In these cases the paths passed through by P are such that P comes closer to E near S, and S, than at S, and S, in figure 24 (i.e., the apparent size of P as viewed from E varies), and that P seems to slow down and reverse its motion (i.e., move in a retrograde motion) in figure 25.

Ptolemy used combinations of epicycles and deferents to account for several features of planetary motions, including the variable sizes and retrogradations. Unfortunately, no simple combination of a single epicycle with a single deferent was able to account for the motions of most heavenly bodies, so Ptolemy moved the center of the deferent away from the earth (i.e., made the deferent an eccentric circle) and/or added a second epicycle moving on the first to account for some motions—especially those of Mars and of the moon. Even this technique was unable to produce a system that fully accounted for all apparent motions; so Ptolemy adopted a final mathematical technique. He made the angular motion of the center C of the epicycle for some planets constant about another point, \( \text{Eq} \), which we call the equant, and which is neither the Earth nor the center of the deferent (see figure 26). This technique allowed him to
produce the proper variations of apparent angular motion for all planets and at all points in their orbits.

Through the use of eccentric circles, deferents, epicycles, and equants, and with the proper choices of eccentricities, angular velocities, equant placements and initial positions, Ptolemy was able to provide a scheme for calculating the observed positions of heavenly bodies which indeed "saved the phenomena" during the period immediately after he lived. But by the period of the Renaissance, two classes of critical problems had arisen.

The first set of problems arose out of the fact that planetary, solar, and lunar positions as calculated according to Ptolemaic theory simply did not correspond to those actually observed; this produced problems for the religious calendar and for astrological prognostication. The calculated conjunctions of planets were frequently several days out of phase with observation, and Easter was out of phase by about ten days with respect to the spring equinox by the early sixteenth century, causing the church to call a council on calendar reform in 1512. At this meeting a young Polish astronomer, Nicolas Copernicus, advised against calendar reform until astronomical theory could be revised.

A second set of problems for Renaissance astronomy grew out of observations made in Islam. These observations suggested that the relationship between solar and sidereal years was not constant. A solar year is defined as the period between successive spring equinoxes. A sidereal year is defined as the period between successive passages of the sun past a specified point on the sphere of the fixed stars. Hipparchus and Ptolemy both realized that these two year lengths were different, and that the point of the spring equinox moves (precesses) through the fixed stars at the rate of about 1° per century. Since the ratio between the two year lengths was presumed to be
constant, however, there was no problem in moving from positions measured relative to the sun (synodic) and those measured relative to the stars (sidereal). The sidereal period of any motion was simply the synodic period times the ratio of sidereal to solar years.

In fact, the sidereal and solar years are nearly constantly related, but a series of erroneously recorded Islamic and ancient observations indicated that they were not; and neither Copernicus nor any of his near contemporaries doubted the validity of those observations. Consequently, either one had to assume that the solar year varied over time or that the sidereal year varied (i.e., that the motion of the sphere of the fixed stars was inconstant). Ptolemy made the first assumption, and later Ptolemaic astronomers tried to account for the variation (trepidation) of the motion of the fixed stars. Figure 27 indicates a mechanism proposed by Purbach, for example.

Copernicus seems to have been particularly bothered by the Ptolemaic assumption of constant solar years and hence variable motion of the fixed stars. Certainly, such an assumption violated all earlier arguments about the peculiar perfection and constancy of stellar motion that came from natural philosophy—whether Platonic or Aristotelian. But even more critically, Copernicus felt that since virtually all motions of planets—including the motion of the sun itself—were observed against the background of the fixed stars, it was self-contradictory to suppose that the "fixed" reference system moved with an inconstant velocity. For whatever reasons, in all of his attempts at astronomical reform Copernicus began from the assumption of a constant sidereal year. "Equal Motion should be Measured Not by the Equinoxes but by the Fixed Stars," he wrote.

Once set on the task of revising astronomical theory, Copernicus took the natural humanistic tack of reviewing older theories.

I therefore took pains to read again the works of all the philosophers on whom I could lay hand to seek out whether any of them had ever supposed that the motions of the spheres were other than those demanded by the mathematical schools. I found first in Cicero that Hecataeus had realized that the earth moved. Afterwards I found in Plutarch that certain others had held the like opinion. I think fit here to add Plutarch's own words, to make them accessible to all:—

"The earth held the earth to be stationary, but Philolaus the Pythagorean says that she moves around the (central) fire on an oblique circle like the Sun and Moon. Heraclides of Pontus and Ephydander the Pythagorean also make the earth to move, not indeed through space but by rotating round her own centre as a wheel on an axle from West to East."

Taking advantage of this, I, too, began to think of the mobility of the earth; and though the opinion seemed absurd, yet knowing now that others before me had been granted freedom to imagine such circles as they chose to explain the phenomena of the stars, I considered that I also might easily be allowed to try whether, by assuming some motion of the earth, sounder explanations than theirs for the revolution of the Celestial spheres might be discovered.

The preliminary version of Copernicus' new theory appeared in The Commentariolus which was composed sometime before the mid-1520's, and while the masterful De Revolutionibus somewhat modifies and greatly extends the approach taken in The Commentariolus, the earlier text contains the most fundamental non-technical aspects of Copernicus' works in a form that is much more readable for nonmathematicians than the great masterpiece. In particular, it presents the essence of Copernicanism in the form of seven basic assumptions:

1. There is no one center of all the celestial circles or spheres.
2. The center of the earth is not the center of the universe, but only of gravity and of the lunar sphere.
3. All the spheres revolve about the sun as their mid-point, and therefore the sun is the center of the universe.

4. The ratio of the earth's distance from the sun to the height of the firmament is so much smaller than the ratio of the earth's radius to its distance from the sun that the distance from the earth to the sun is imperceptible in comparison with the height of the firmament.

5. Whatever motion appears in the firmament arises not from any motion of the firmament, but from the earth's motion. The earth together with its circumjacent elements performs a complete rotation on its fixed poles in a daily motion, while the firmament and highest heaven abide unchanged.

6. What appear to us as motions of the sun arise not from its motion but from the motion of the earth and our sphere, with which we revolve about the sun like any other planet. The earth has, then, more than one motion.

7. The apparent retrograde and direct motion of the planets arises not from their motion but from the earth's. The motion of the earth alone, therefore, suffices to explain so many apparent inequalities in the heavens.27

The resulting system (for motions along the ecliptic) can be presented as in figure 28.

If we consider the Copernican and Ptolemaic systems solely as mathematical calculating systems, they are equivalent systems for predicting observed positions of the planets, the moon and the sun. Because Copernicus had the advantage of establishing new initial positions and refined period relations, his system produced more accurate tables of position than Ptolemy's; but that was not the result of a changed system of calculation.

The Copernican scheme did, however, offer some advantages over that of Ptolemy. Though it involved about the same number of deferents and epicycles, it managed to avoid using equants. Furthermore it (1) allowed for a more natural explanation of retrograde motions based on the differential velocities of the earth and other planets; (2) provided a natural explanation of the fact that the observed periods of the sun, Venus, and Mercury were the same; (3) provided a natural progression from the fastest to the slowest motions as the distance from the sun increased; and (4) provided a means for determining the relative sizes of planetary orbits.

From a strictly mathematical point of view, only two major inconveniences accompanied these gains. First, a mathematical theory that posits only a single center of all motions is aesthetically preferable to one that posits several centers—so assumption one of The Commentariolis is a net loss from the mathematical point of view. Second, since all positions are observed from the earth it is necessary in Copernican astronomy to do some time-consuming trigonometric calculations to move to positions as viewed from the sun and back—but this is a purely computational inconvenience.

Had astronomers been able to evaluate the Copernican system strictly as a calculating scheme with no broader implications for natural philosophy and other topics tied to cosmology, they probably would have rapidly accepted it. But it seems clear that Copernicus neither intended his work to be devoid of philosophical implications,28 nor that many readers were able to read it without seeing that if accepted, it would directly overturn virtually all traditional natural philosophy and cosmology and indirectly disrupt the rationales for such overarching schemes as those associated with macrocosm-microcosm correspondences.

Andreas Osiander, who took on the task of publication of De Revolutionibus for an aging and ill Copernicus, foresaw the likely problems and tried to forestall them by adding an anonymous "letter
to the reader” denying that any philosophical implications should be imputed to the work, which was to be viewed solely as a calculating scheme based on assumptions that were not supposed to reflect reality. “I have no doubt,” he wrote, “that some learned men have taken serious offence because the book declares that the earth moves and that the sun is at rest in the center of the universe; these men undoubtedly believe that the liberal arts, established long ago on a correct basis, should not be thrown into confusion.”

Such men should have no fear, Osiander continued, “For it is quite clear that the causes of apparent unequal motions are completely and simply unknown to this art. And if any causes are devised by the imagination, as indeed very many are, they are not put forward to convince any one that they are true, but merely to provide a correct basis for calculation.”

Regardless of Osiander’s claims, most readers could not read Copernicus without seeing that his work denied, among other longstanding assumptions, the fundamental presumption of a hierarchical spatial ordering of the cosmos from the highest Divine sphere to the lowest terrestrial sphere. Consequently, the largest potential audience for Copernicus’ work, the class of medical-astrologers, found Copernicanism incompatible with their most fundamental beliefs; and they naturally rejected it.

POLITICAL AND THEOLOGICAL IMPLICATIONS OF COPERNICAN THEORY

Even more importantly, the tendency to view microcosmic-macrocosmic correspondences as the foundation of the understanding of all orders of existence—especially of the political and social orders of human existence—was of overwhelming importance during the Renaissance. And this tendency inextricably linked cosmological and political attitudes in such a way that a series of simple technical changes in astronomy could seem to threaten both the ability to understand politics and society, and the very stability of society itself.

Images of correspondence between heavenly hierarchies and social ones, and between the microcosm, man, and the macrocosm, state, provided the central arguments of conservative political ideology during the late sixteenth and very early seventeenth centuries. “This is Nature’s nest of boxes,” wrote John Donne in one of his sermons, “The Heavens contain the Earth, the Earth cities, Cities, Men. And all these are concentric.” From this concentricity one recognized how the plan of each successive internal order mirrored the plans of those superior to it.

This notion provided a rationale for aristocratic social and political hierarchies for the authors of late Renaissance court literature, and for those who defended a hierarchical structure of church government against those who sought a more democratic arrangement. But to illustrate the pervasiveness and power of the linkage between celestial and social orders there is no better place to start than with the famous speech of Ulysses from Shakespeare’s Troilus and Cressida, written shortly before 1603.

In this speech, Ulysses explains to his Greek countrymen why they have failed to capture Troy in spite of their supposed superiority in numbers and military training. Greek military discipline has broken down and confusion has arisen because the great Greek general, Achilles, has not behaved in a manner proper to his station.

The specialty of rule hath been neglected.
And look how many Grecian tents do stand
Hollow upon this plain, so many hollow factions.
When that the general is not like the hive
To whom the foragers shall all repair,
What honey is expected? Degree being obscured . . .
The heavens themselves, the planets and this
center,
Observe degree, priority, and place,