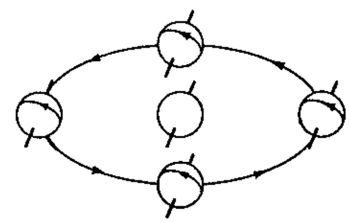
THE COPERNICAN REVOLUTION

Planetary Astronomy in the Development of Western Thought



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scend to earth far from the point where his leap began, for the earth would move beneath him while he was in the air. Rocks and trees, cows and men must be hurled from a rotating earth as a stone flies from a rotating sling. Since none of these effects is seen, the earth is at rest. Observation and reason have combined to prove it.

Today in the Western world only children argue this way, and only children believe that the earth is at rest. At an early age the authority of teachers, parents, and texts persuades them that the earth is really a planet and in motion; their common sense is reëducated; and the arguments born from everyday experience lose their force. But reëducation is essential – in its absence these arguments are immensely persuasive – and the pedagogic authorities that we and our children accept were not available to the ancients. The Greeks could only rely on observation and reason, and neither produced evidence for the earth's motion. Without the aid of telescopes or of elaborate mathematical arguments that have no apparent relation to astronomy, no effective evidence for a moving planetary earth can be produced. The observations available to the naked eye fit the two-sphere universe very well (remember the universe of the practical navigator and surveyor), and there is no more natural explanation of them. It is not hard to realize why the ancients believed in the two-sphere universe. The problem is to discover why the conception was given up.

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THE PROBLEM OF THE PLANETS

Apparent Planetary Motion

If the sun and stars were the only celestial bodies visible to the naked eye, modern man might still accept the fundamental tenets of the two-sphere universe. Certainly he would have accepted them until the invention of the telescope, more than half a century after Copernicus' death. There are, however, other prominent celestial bodies, particularly the planets, and the astronomer's interest in these bodies is the principal source of the Copernican Revolution. Once again we consider observations before dealing with interpretive explanations. And once again the discussion of interpretations will confront us with a new and fundamental problem about the anatomy of scientific belief.

The term planet is derived from a Greek word meaning "wanderer," and it was employed until after Copernicus' lifetime to distinguish those celestial bodies that moved or "wandered" among the stars from those whose relative positions were fixed. For the Greeks and their successors the sun was one of the seven planets. The others were the moon, Mercury, Venus, Mars, Jupiter, and Saturn. The stars and these seven planets were the only bodies recognized as celestial in antiquity. No additional planets were discovered until 1781, long after the Copernican theory had been accepted. Comets, which were well known in the ancient world, were not considered celestial bodies before the Copernican Revolution (Chapter 6).

All of the planets behave somewhat like the sun, though their motions are uniformly more complex. All have a westward diurnal motion with the stars, and all move gradually eastward among the stars until they return to approximately their original positions. Throughout their motions the planets stay near the ecliptic, sometimes wandering north of it, sometimes south, but very seldom leaving the band of the zodiac, an imaginary strip in the sky extending for 8° on either side of the ecliptic. At this point the resemblance between planets ends, and the study of planetary irregularities begins.

The moon travels around the ecliptic faster and less steadily than the sun. On the average it completes one journey through the zodiac in 27⅓ days, but the time required for any single journey may differ from the average by as much as 7 hours. In addition, the appearance of the moon's disk changes markedly as it moves. At new moon its disk is completely invisible or very dim; then a thin bright crescent appears, which gradually waxes until, about a week after new moon, a semicircular sector is visible. About 2 weeks after new moon the full circular disk appears; then the cycle of phases is reversed, and the moon gradually wanes, reaching new moon again about 1 month after the preceding new moon. The cycle of phases is recurrent, like the moon's journey through the signs of the zodiac, but the two lunar cycles are significantly out of step. New moon recurs after an average interval of 29½ days (individual cycles may differ by as much as ½ day from this average), and, since this is 2 days longer than the period of an average journey around the zodiac, the position of successive new moons must gradually move eastward through the constellations. If new moon occurs at the position of the vernal equinox one month, the moon will still be waning when it returns to the vernal equinox 27⅓ days later. New moon does not recur for about 2 days more, by which time the moon has moved almost 30° east from the equinox.

Because they are easily visible and conveniently spaced, the moon's phases provided the oldest of all calendar units. Primitive forms of both the week and the month appear in a Babylonian calendar from the third millennium B.C., a calendar in which each month began with the first appearance of the crescent moon and was subdivided at the 7th, 14th, and 21st days by the recurrent "quarters" of the moon's cycle. At the dawn of civilization men must have counted new moons and quarters to measure time intervals, and as civilization progressed they repeatedly attempted to organize these fundamental units into a coherent long-term calendar — one that would permit the compilation of historical records and the preparation of contracts to be honored at a specified future date.

But at this point the simple obvious lunar unit proved intractable. Successive new moons may be separated by intervals of either 29 or 30 days, and only a complex mathematical theory, demanding generations of systematic observation and study, can determine the length of a specified future month. Other difficulties derive from the incommensurable lengths of the average lunar and solar cycles. Most societies (but not all, for pure lunar calendars are still used in parts of the Middle East) must adjust their calendars to the sun-governed annual climatic variation, and for this purpose some systematic method for inserting an occasional thirteenth month into a basic year of 12 lunar months (354 days) must be devised. These seem to have been the first difficult technical problems encountered by ancient astronomy. More than any others, they are responsible for the birth of quantitative planetary observation and theory. The Babylonian astronomers who finally solved these difficulties between the eighth and third centuries B.C., a period during most of which Greek science was still in its infancy, accumulated much of the fundamental data subsequently incorporated into the developed structure of the two-sphere universe.

Unlike the moon and sun, the remaining five planets appear as mere points of light in the heavens. The untrained naked-eye observer can distinguish them from stars with assurance only by a series of observations that discloses their gradual motion around the ecliptic. Usually the planets move eastward through the constellations: this is their so-called "normal motion." On the average, both Mercury and Venus require 1 year for each complete circuit of the zodiac; the length of Mars's cycle averages 687 days; Jupiter's average period is 12 years; and Saturn's is 29 years. But in all cases the time required for any single journey may be quite different from the average period. Even when moving eastward through the stars, a planet does not continue at a uniform rate.

Nor is its motion uniformly eastward. The normal motion of all planets except the sun and moon is occasionally interrupted by brief intervals of westward or "retrograde" motion. Compare Mars retrogressing in the constellation Taurus, shown in Figure 15, with the normal motion of the sun through Taurus, shown in Figure 9 (p. 22). Mars enters the diagram in normal (eastward) motion, but as its motion continues, the planet gradually slows until at last it reverses its direction and begins to move westward, in retrograde. Other planets behave in much the same way, each one repeating the interlude of retrograde motion after a fixed length of time. Mercury briefly reverses its motion through the stars once every 116 days, and Venus retrogresses every 584 days. Mars, Jupiter, and Saturn show retrograde motion every 780, 399, and 378 days, respectively.

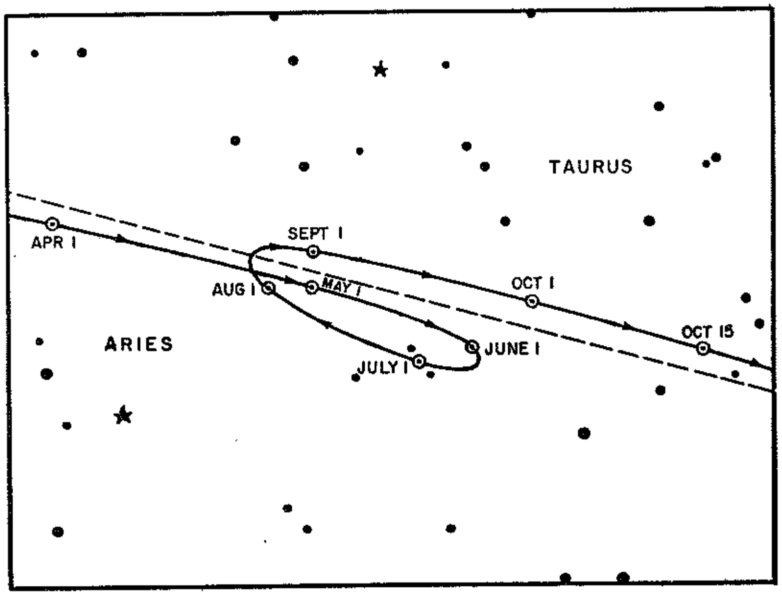

Figure 15. Mars retrogressing in Aries and Taurus. The section of sky is the same as that shown in Figure 9 and in the box on the star map of Figure 8. The broken line is the ecliptic and the solid line the path of the planet. Note that Mars does not stay on the ecliptic and that, though its over-all motion is eastward among the stars, there is a period from the middle of June to early August during which it moves to the west. The retrogressions of Mars are always of approximately this form and duration, but they do not always occur on the same date or in the same part of the sky.

In their gradual eastward motions interrupted by periodic westward retrogressions, the five wandering stars behave quite similarly. But there is an additional characteristic of their motion which divides them into two groups; this is the correlation between their position and the sun's. Mercury and Venus, the two so-called inferior planets, never get very far from the sun. Mercury is always found within 28° of the sun's moving disk, and Venus's maximum "elongation" is 45°. Both planets move in a continuous slow shuttle, back and forth across the

moving sun; for a time they move eastward with the sun, then retrogress across its disk, and finally reverse themselves to overtake the sun once more. When to the east of the sun, either of these inferior planets appears as an "evening star," becoming visible shortly after sunset and then rapidly following the sun below the horizon. After retrogressing westward across the sun's disk, the planet becomes a "morning star," rising shortly before dawn and disappearing in the brilliant light of sunrise. But in between, when close to the sun, neither Mercury nor Venus can be seen at all. Therefore, until their motion was analyzed with respect to the sphere of the stars, neither of the inferior planets was recognized as the same celestial body when it appeared as a morning and as an evening star. For millenniums Venus had one name when it rose in the east shortly before dawn and another when, weeks later, it again became visible just over the western horizon shortly after sunset.

Unlike Mercury and Venus, the superior planets, Mars, Jupiter, and Saturn, are not restricted to the same part of the sky as the sun. Sometimes they are very close to or "in conjunction" with it; at other times they are 180° across the sky or "in opposition" to the sun; between these times they assume all the intermediate positions. But though their positions are unrestricted, their behavior does depend upon their relation to the sun. Superior planets retrogress only when they are in opposition. Also, when in retrograde motion across the sky from the sun, superior planets appear brighter than at any other time. This increased brilliance, which has usually been interpreted (at least since the fourth century B.C.) as indicating a decrease in the planet's distance from the earth, is particularly striking in the case of Mars. Normally a relatively inconspicuous planet, Mars in opposition will frequently outshine every celestial body in the night sky except the moon and Venus.

Interest in the five wandering stars is by no means so ancient as a concern with the sun and moon, presumably because the wandering stars had no obvious practical bearing upon the lives of ancient peoples. Yet observations of the appearance and disappearance of Venus were recorded in Mesopotamia as early as 1900 B.C., probably as omens, portents of the future, like the signs to be read in the entrails of sacrificial sheep. These scattered observations presage the much later development of systematic astrology, a means of forecasting whose intimate relation to the development of planetary astronomy is considered in the next chapter. The same concern with omens clearly motivated the more systematic and complete records of eclipses, retrograde motions, and other striking planetary phenomena compiled by Babylonian observers after the middle of the eighth century B.C. Ptolemy, the dean of ancient astronomers, later complained that even these records were fragmentary, but fragmentary or not they provided the first data capable of specifying the full-scale problem of the planets as that problem was to develop in Greece after the fourth century B.C.

The problem of the planets is partially specified by the description of the planetary motions sketched in the preceding pages. How are the complex and variable planetary motions to be reduced to a simple and recurrent order? Why do the planets retrogress, and how account for the irregular rate of even their normal motions? These questions indicate the direction of most astronomical research during the two millenniums from the time of Plato to the time of Copernicus. But because it is almost entirely qualitative, the preceding description of the planets does not specify the problem fully. It states a simplified problem and in some respects a misleading one. As we shall shortly see, qualitatively adequate planetary theories are easily invented: the description above can be reduced to order in several ways. The astronomer's problem, on the other hand, is by no means simple. He must explain not merely the existence of an intermittent westward motion superimposed upon an over-all eastward motion through the stars, but also the precise position that each planet occupies among the stars on different days, months, and years over a long period of time. The real problem of the planets, the one that leads at last to the Copernican Revolution, is the quantitative problem described in lengthy tables which specify in degrees and minutes of arc the varying position of every planet.

The Location of the Planets

The two-sphere universe, as developed in the last chapter, provided no explicit information about the positions or motions of the seven planets. Even the sun's location was not discussed. To appear "at" the vernal equinox (or any other point on the stellar sphere) the sun need merely be somewhere on a line stretching from the observer's eye to or through the appropriate point in the background of stars.

Like the other planets, it might be either inside, on, or perhaps even outside the sphere of the stars. But though the two-sphere universe fails to specify the shape or location of the planetary orbits, it does make certain choices of position and orbit more plausible than others, and it therefore at once guides and restricts the astronomer's approach to the problem of the planets. That problem was set by the results of observation, but, from the fourth century B.C., it was pursued in the conceptual climate of two-sphere cosmology. Both observation and theory made essential contributions to it.

Within a two-sphere cosmology, for example, the planetary orbits should if possible preserve and extend the fundamental symmetry embodied in the first two spheres. Ideally the orbits should therefore be earth-centered circles, and the planets should revolve in these circles with the same regularity that is exemplified in the rotation of the stellar sphere. The ideal does not quite conform to observation. As we shall see presently, an earth-centered circular orbit located in the plane of the ecliptic provides a good account of the sun's annual motion, and a similar circle can give an approximate account of the somewhat less regular motion of the moon. But circular orbits do not even hint at an explanation of the gross irregularities, like retrogression, observed in the motions of the other five wandering "stars." Nevertheless, astronomers who believed in the two-sphere universe could, and for centuries did, think that earth-centered circles were the natural orbits for planets. Such orbits at least accounted for the over-all average eastward motions. Observed deviations from the average motion – changes in the rate or direction of a planet's motion – indicated that the planet itself had deviated from its natural circular orbit, to which it would again return. On this analysis the problem of the planets became simply that of explaining the observed deviation from average motion through the stars in terms of a corresponding deviation of each planet from its single circular orbit.

We shall examine some of the ancient explanations of these deviations in the next three sections, but first notice, as the ancients also did, how far it is possible to proceed by neglecting the planetary irregularities and assuming simply that all orbits are at least approximately circular. Almost certainly, in the two-sphere universe, the planets move in the region between the earth and the stars. The stellar sphere itself was often viewed as the outer boundary of the universe, so that the planets could not be outside it; the difference between planetary and stellar motions indicated that the planets were probably not located on the sphere, but in some intermediate region where they were affected by some influence that was inactive at the stellar sphere; the whole argument gained force from the detail visible on the face of the moon, presumptive evidence that one planet, at least, must be nearer than the stars. Ancient astronomers, therefore, laid out the planetary orbits in that vast and previously empty space between the earth and the sphere of the stars. By the end of the fourth century B.C., the two-sphere universe was filling up. Later it was to become crowded.

Once the general location and shape of their orbits were known, it proved possible to make a plausible and satisfying guess about the order in which the planets were arranged. Planets like Saturn and Jupiter, whose eastward motion was slow and whose total motion, therefore, very nearly kept pace with the stars, were supposed to be close to the stellar sphere and far from the earth. The moon, on the other hand, which loses over 12° a day in its race with the stars, must be closer to the stationary surface of the earth. Some ancient philosophers seem to have justified this hypothetical arrangement by imagining that the planets floated in a gigantic aethereal vortex, whose outer surface moved rapidly with the sphere of the stars and whose interior was at rest at the earth's surface. Any planet caught in such a vortex would lose more ground with respect to the stellar sphere if it were closer to the earth. Other philosophers reached the same conclusion by a different sort of argument, later recorded, at least in its essentials, by the Roman architect Vitruvius (first century B.C.). In analyzing the differences between the intervals required by different planets for trips about the ecliptic, Vitruvius suggested an illuminating analogy:

> Place seven ants on a wheel such as potters use, having made seven channels on the wheel about the center, increasing successively in circumference; and suppose those ants obliged to make a circuit in these channels while the wheel is turned in the opposite direction. In spite of having to move in a direction contrary to that of the wheel, the ants must necessarily complete their journeys in the opposite direction, and that ant which is nearest the center must finish its circuit sooner, while the ant that is going round at the outer edge of the disk of the wheel must, on account of the size of its circuit, be much slower in completing its course, even though it is moving just as quickly as the other. In the same way, these stars, which struggle on against the course of the firmament, are accomplishing an orbit on paths of their own; but, owing to the revolution of the heaven, they are swept back as it goes round every day.[1]

Before the end of the fourth century B.C., arguments like the above had led to an image of the universe similar to the one sketched in Figure 16; diagrams like this, or their verbal equivalents, remained current in elementary books on astronomy or cosmology until the early seventeenth century, long after Copernicus' death. The earth is at the center of the stellar sphere, which bounds the universe; immediately inside this outer sphere is the orbit of Saturn, the planet that takes longest to move around the zodiac; next comes Jupiter and then Mars.

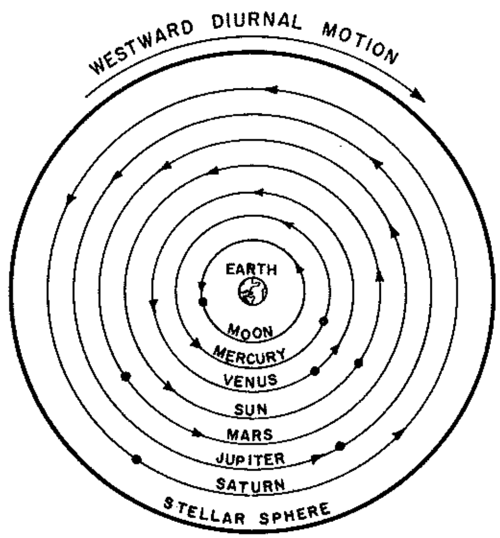

Figure 16. Approximate planetary orbits in the two-sphere universe. The outermost circle is a cross section of the stellar sphere in the plane of the ecliptic.

To this point the order is unambiguous: the planets are arranged, from the outside, in the order of decreasing orbital period; the same technique places the lunar orbit closest to the earth. But the remaining three planets present a problem; the sun, Venus, and Mercury all complete their journeys about the earth in the same average time, 1 year, and their order therefore cannot be determined by the device applied to the other planets. There was, in fact, much disagreement about their order during antiquity. Until the second century B.C. most astronomers placed the sun's orbit just outside the moon's, Venus's outside the sun's, then Mercury's, and then Mars's. After that date, however, the order shown in the diagram – moon, Mercury, Venus, sun, Mars, etc. – became increasingly popular. In particular, it was adopted by Ptolemy, and his authority imposed it upon most of his successors. We shall therefore take this order as standard throughout the early chapters of this book.

As a structural diagram Figure 16 is still very crude. It gives no meaningful indication of relative dimensions of the various orbits, and it makes no attempt to provide for the observed planetary irregularities. But the conception of the universe embodied in the diagram had two important functions in the subsequent development of astronomy and cosmology. In the first place, the diagram contains most of the structural information about the earth-centered universe that ever became common knowledge among nonastronomers. The further achievements of ancient astronomy, to which we shall turn in a moment, were too mathematical for most laymen to understand. As the next two chapters indicate more fully, the most influential cosmologies developed in antiquity and the Middle Ages did not follow ancient astronomy very far beyond this point. Astronomy now becomes esoteric; its further development does not provide man with a home.

In addition, the structural diagram in Figure 16 is, despite its crudity, an immensely powerful tool in astronomical research. For many purposes it proved both economical and fruitful. For example, during the fourth century B.C., the concepts embodied in the diagram provided a complete qualitative explanation of both the phases of the moon and lunar eclipses; during the fourth and third centuries these same concepts led to a series of relatively accurate determinations of the circumference of the earth; and during the second century B.C., they provided the basis for a brilliantly conceived estimate of the sizes and distances of the sun and moon. These explanations and measurements, particularly the last, typify the immense ingenuity and power of the ancient astronomical tradition. They are, however, here relegated to the Technical Appendix (Sections 3 and 4), because they were not affected by the change in astronomical theory during the Copernican Revolution. Nevertheless, they are relevant to the Revolution. The ability of the developed two-sphere universe to explain and ultimately to predict prominent celestial phenomena like eclipses, as well as its

ability to specify some linear dimensions of the celestial regions, immeasurably increased the hold of the two-sphere conceptual scheme upon the minds of both astronomers and laymen.

These achievements do not, however, touch upon the fundamental problem posed by the continuous irregularity of planetary motion, and this problem provides the pivot upon which the Copernican Revolution ultimately turns. Like so many other problems of ancient astronomy, it seems first to have emerged during the fourth century B.C., when the two-sphere universe, by explaining diurnal motion, enabled Greek astronomers to isolate the residual planetary irregularities for the first time. During the following five centuries successive attempts to explain these irregularities produced several planetary theories of unprecedented accuracy and power. But these attempts also constitute the most abstruse and mathematical part of ancient astronomy, and they are therefore usually omitted from books like this. Though a simplified précis of ancient planetary theory seems a minimal requisite for an understanding of the Copernican Revolution, a few readers may prefer to skim the next three sections (particularly the first, in which the technical presentation is especially compact), picking up the narrative again with the discussion of scientific belief that closes this chapter.

The Theory of Homocentric Spheres

The philosopher Plato, whose searching questions dominated so much of subsequent Greek thought, seems to have been the first to enunciate the problem of the planets, too. Early in the fourth century B.C. Plato is said to have asked: "What are the uniform and ordered movements by the assumption of which the apparent movements of the planets can be accounted for?" [2] and the first answer to this question was provided by his onetime pupil Eudoxus (*c.*408 – *c.*355 B.C.). In Eudoxus' planetary system each planet was placed upon the inner sphere of a group of two or more interconnected, concentric spheres whose simultaneous rotation about different axes produced the observed motion of the planet. Figure 17*a* shows a cross section of two such interlocked spheres whose common center is the earth and whose points of contact are the ends of the slanted axis of the inner sphere, which serve as pivots. The outer sphere is the sphere of the stars, or at least it has the same motion as that sphere; its axis passes through the north and south celestial poles, and it rotates westward about this axis once in 23 hours 56 minutes. The inner sphere's axis makes contact with the outer sphere at two diametrically opposite points 23½° away from the north and south celestial poles; therefore the equator of the inner sphere, viewed from the earth, always falls on the ecliptic of the sphere of the stars, regardless of the rotation of the two spheres.

If the sun is now placed at a point on the equator of the inner sphere and that sphere is turned slowly eastward about its axis once in a year while the outer sphere turns about its axis once a day, the sum of the two motions will reproduce the observed motion of the sun. The outer sphere produces the observed westward diurnal motion of rising and setting; the inner sphere produces the slower annual eastward motion of the sun, around the ecliptic. Similarly, if one eastward rotation of the inner sphere occurs every 27⅓ days and if the moon is placed on the equator of this sphere, then the motion of this inner sphere must produce the average motion of the moon around the ecliptic. The north and south deviations of the moon from the ecliptic and some of the irregularities in the time required by the moon for successive journeys can be approximated by adding one more very slowly moving sphere to the system. Eudoxus also used (though unnecessarily) a third sphere to describe the motion of the sun, so that six spheres were required to treat the moon and sun together.

The spheres shown in Figure 17*a* were known as homocentric spheres, because they have a common center, the earth. Two or three such spheres can approximately represent the total motion of the sun and of the moon, but they cannot account for the retrograde motions of the planets, and Eudoxus' greatest genius as a geometer was displayed in the modification of the system that he introduced in treating the apparent behavior of the remaining five planets. For each of these he used a total of four spheres, sketched in cross section in Figure 17*b*. The two outer spheres move just like the spheres of Figure 17*a*: the outer sphere has the diurnal motion of the sphere of the stars and the second sphere (counting from the outside) turns eastward once in the *average* time required by the planet to complete a journey around the ecliptic. (Jupiter's second sphere, for example, turns once in 12 years.) The third sphere is in contact with the second sphere at two diametrically opposite points on the ecliptic (the equator of the second sphere), and the axis of the fourth or innermost sphere is fastened to the third sphere at an angle that depends upon the

characteristics of the motion to be described. The planet itself (Jupiter in the example above) is located on the equator of the fourth sphere.

Suppose now that the two outer spheres are held stationary and that the two innermost spheres rotate in opposite directions, each completing one axial rotation in the interval that separates two suc-

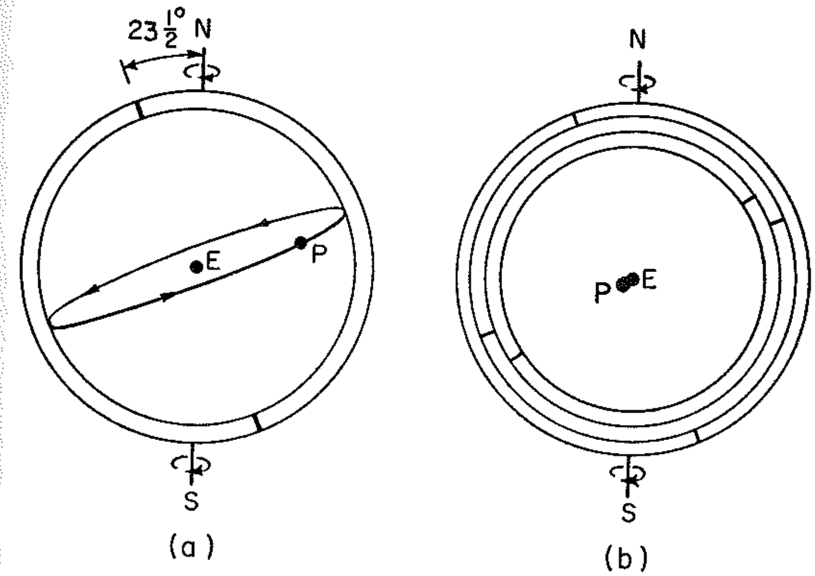

Figure 17. Homocentric spheres. In the two-sphere system (*a*) the outermost sphere produces the diurnal rotation, and the inner sphere moves the planet (sun or moon) steadily eastward around the ecliptic. In the four-sphere system (*b*) the planet *P* lies out of the plane of the paper, almost on a line from the earth *E* to the reader's eye. The two innermost spheres then produce the looped motion shown in Figure 18, and the two outer spheres produce both the diurnal motion and the average eastward planetary drift.

cessive retrogressions of the planet (399 days for Jupiter). An observer watching the motion of the planet against the temporarily stationary second sphere will see it move slowly in a figure eight, both of whose loops are bisected by the ecliptic. This is the motion sketched in Figure 18; the planet passes slowly around the loops from positions 1 to 2, 2 to 3, 3 to 4, . . . , spending equal times between each numbered point and the next, and returning to its starting point after the interval between retrogressions. During its motion from 1 to 3 to 5 the planet moves eastward along the ecliptic; during the other half of the time, while the planet moves from 5 to 7 and back to 1, it moves westward.

Now allow the second sphere to rotate eastward, carrying the two rotating inner spheres with it, and suppose that the total motion of the planet is observed against the background of stars on the first sphere, again held temporarily stationary. At all times the planet is moved eastward by the motion of the second sphere, and half of the time (while it moves from 1 to 5 in Figure 18) the planet receives an additional eastward motion from the two inner spheres so that its net motion is eastward and even more rapid than that of the second sphere alone. But during the other half of the time (as the planet moves from 5 to 1 in Figure 18) the eastward motion of the second sphere is opposed by a westward motion due to the two inner spheres, and, when this westward motion is most rapid (near 7 in Figure 18), the net motion of the planet against the sphere of the stars may actually be to the west, in the retrograde direction. This is just the characteristic of observed planetary motions that Eudoxus was striving to reproduce in his model.

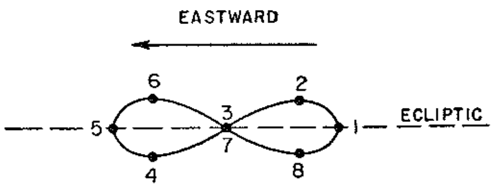

Figure 18. The looped motion generated by the two innermost homocentric spheres. In the full four-sphere system this looped motion is combined with the steady eastward motion of the second sphere, a motion that by itself would carry the planet around the ecliptic at a uniform rate. When the looped motion is added, the total motion of the planet varies in rate and is no longer confined to the ecliptic. While the planet moves from 1 to 5 on the loop, its total motion is more rapid than the average eastward motion generated by the second sphere; while the planet moves back from 5 to 1 on the loop, its eastward motion is slower than that produced by the second sphere, and when it gets near 3, it may actually move westward, in retrograde.

A system of four interlocked homocentric spheres approximates the retrograde motion of Jupiter, and a second set of four spheres can account for the motion of Saturn. For each of the three remaining planets, five spheres are needed (an extension provided by Eudoxus' successor Callippus around 330 B.C.), and analysis of the resulting motions becomes correspondingly more complex. Fortunately, we need not pursue these complex combinations of rotating spheres further, because all homocentric systems have one severe drawback which in antiquity led to their early demise. Since Eudoxus' theory places each planet on a sphere concentric with the earth, the distance between a planet and the earth cannot vary. But planets appear brighter, and therefore seem closer to the earth, when they retrogress. During antiquity the homocentric system was frequently criticized for its failure to explain this variation in planetary brilliance, and the system was abandoned by most astronomers almost as soon as a more adequate explanation of the appearances was proposed.

But though short-lived as a significant astronomical device, homocentric spheres play a major role in the development of astronomical and cosmological thought. By a historical accident the century during which they seemed to provide the most promising explanation of planetary motion embraced most of the lifetime of the Greek philosopher Aristotle, who incorporated them in the most comprehensive, detailed, and influential cosmology developed in the ancient world. No comparably complete cosmology ever incorporated the mathematical system of epicycles and deferents which, in the centuries after Aristotle's death, was employed to explain planetary motion. The conception that planets are set in rotating spherical shells concentric with the earth remained an accepted portion of cosmological thought until early in the seventeenth century. Even the writings of Copernicus show important vestiges of this conception. In the title of Copernicus' great work, *De Revolutionibus Orbium Caelestium*, the "orbs" or spheres are not the planets themselves but rather the concentric spherical shells in which the planets and the stars are set.

Epicycles and Deferents

The origin of the device that replaced homocentric spheres in explaining the details of planetary motion is unknown, but its features were early investigated and developed by two Greek astronomers and mathematicians, Apollonius and Hipparchus, whose work spans the period from the middle of the third century to the end of the second century B.C. In its simplest form (Figure 19*a*) the new mathematical mechanism for the planets consists of a small circle, the epicycle, which rotates uniformly about a point on the circumference of a second rotating circle, the deferent. The planet, *P*, is located on the epicycle, and the center of the deferent coincides with the center of the earth.

The epicycle-deferent system is intended to explain only motion with respect to the sphere of the stars. Both the epicycle and the deferent in Figure 19*a* are drawn on the plane of the ecliptic, so that the rotation of the stellar sphere carries the entire diagram (except the central earth) through one rotation per day and thus produces the diurnal motion of the planet. If the epicycle and deferent of the figure were stationary and did not have an additional motion of their own, the planet would be fixed in the plane of the ecliptic and would therefore have the motion of a zodiacal star, a westward circle executed once in every 23 hours 56 minutes. From now on, whenever reference is made to the motion of the deferent or the epicycle, it is the *additional* motion of these circles in the plane of the ecliptic that is meant. The diurnal rotation of the sphere and of the plane of the ecliptic will be taken for granted.

Suppose, for example, that the deferent rotates eastward once in a year and that the sun is placed on the deferent at the position now occupied by the center of the epicycle, the epicycle itself being removed. Then the rotation of the deferent carries the sun through its annual journey around the ecliptic, and the sun's motion has been analyzed, at least approximately, in terms of the motion of a single deferent in the plane of the ecliptic. This is the technique taken for granted in the explanation of average planetary motions in Figure 16.

Now imagine that the sun is removed and the epicycle is returned to its position on the deferent. If the epicycle rotates just three times around its moving center while the deferent rotates once and if the two circles rotate in the same direction, then the total motion of the planet within the sphere of the stars produced by the combined motions of the epicycle and the deferent is just the looped curve shown in Figure 19*b*. When the rotation of the epicycle carries the planet outside of the deferent, the motions of both the epicycle and the deferent combine to move the planet to the east. But when the motion of the epicycle places the planet well inside the deferent, the epicycle carries the planet westward, in opposition to the motion of the deferent. Therefore, when the planet is closest to the earth, the two motions may combine to produce a net westward or retrograde motion. In Figure 19*b* the planet retrogresses whenever it is on the interior part of one of the small loops; everywhere else the planet moves normally toward the east, but at a variable rate.

Figure 19*c* shows the motion of the planet through one of the loops as viewed against the sphere of the stars by an observer on earth. Since both observer and loop are in the same plane, that of the ecliptic, the observer cannot see the open loop itself. What he sees is merely the position of the planet against the background provided by the ecliptic. Thus as the planet moves from position 1 to 2 in Figures 19*b* and 19*c*, the observer sees it move along the ecliptic toward the east. As the planet approaches position 2, it appears to move more slowly, stopping momentarily at 2 and then moving westward along the ecliptic as it travels from 2 towards 3. Finally the westward journey of

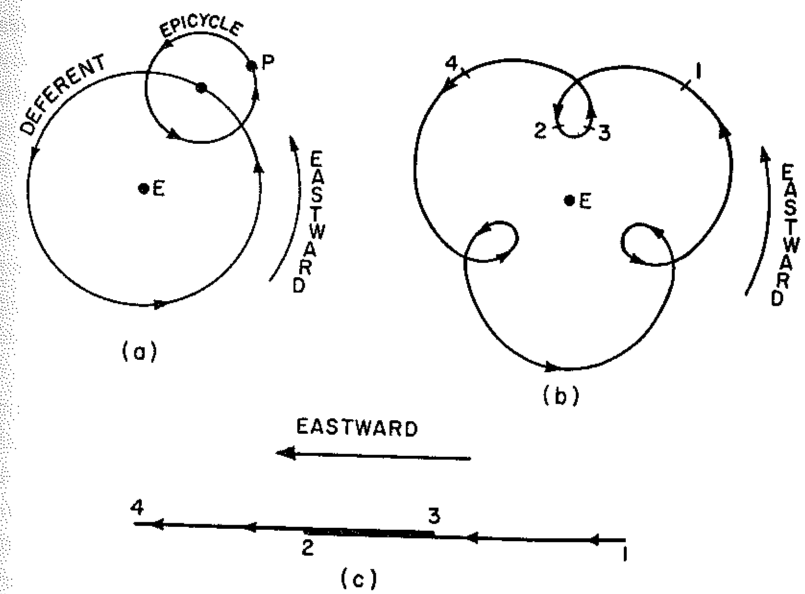

Figure 19. The basic epicycle-deferent system. A typical deferent and epicycle are shown in (*a*); the looped motion that they generate in the plane of the ecliptic is illustrated in (*b*); the third diagram (*c*) shows a portion (1–2–3–4) of the motion in (*b*) as it is seen by an observer on the central earth, *E*.

the planet on the ecliptic halts, and the planet again moves eastward, leaving position 3 on the loop and moving toward 4.

A system of one epicycle and one deferent therefore carries a planet around the ecliptic in an interval that, on the average, exactly equals the time required for one revolution of the deferent. The eastward motion is, however, interrupted and the planet temporarily moves westward at regular intervals equal to the time required for one revolution of the epicycle. The rates of revolution of the epicycle and deferent may be adjusted to fit the observations for any planet, yielding just that intermittent eastward motion among the stars which planets are observed to have. Furthermore, the epicycle-deferent system reproduces one other important qualitative feature of the appearances: a planet can retrogress only when its motion brings it nearest to the earth and that is the position in which the planet should and does appear brightest. Its great simplicity plus this novel explanation of varying planetary brilliance are the primary causes for the new system's victory over the older system of homocentric spheres.

The epicycle-deferent system described by Figure 19 incorporates one special simplification that is not characteristic of the motion of any planet. The epicycle is made to revolve *exactly* three times for each revolution of the deferent. Therefore, whenever the deferent completes one revolution, the epicycle returns the planet to the same position it occupied at the beginning of the revolution; the retrograde loops always occur at the same places; and the planet always requires the same amount of time to complete its trip around the ecliptic. When designed to fit the observations of real planets, however, epicycle-deferent systems never perform in quite this manner. For example, Mercury is observed to require an average of 1 year to complete a journey around the ecliptic, and it retrogresses once every 116 days. Therefore Mercury's epicycle must revolve just over three times while the deferent turns once; the epicycle completes three revolutions in 348 days which is less than the year required for a rotation of the deferent.

Figure 20*a* shows the path of a planet carried through one trip around the ecliptic by an epicycle that turns slightly more than three times for each rotation of its deferent. The planet starts in the middle of a retrograde loop and completes its third full loop before the deferent completes its first full rotation; the planet therefore averages slightly more than three retrograde loops in each trip around the ecliptic. If the motion of Figure 20*a* were continued through a second trip, the new set of retrograde loops would fall slightly to the west of those generated during the first trip. Retrograde motion would not occur at the same position in the zodiac on successive trips, and this is characteristic of the observed progress of planets along the ecliptic.

Figure 20*b* indicates a second characteristic of the motion gen-

erated by an epicycle that does not revolve an integral number of times in each revolution of the deferent. The planet at *P* in the figure is at the position closest to the earth, the position from which the journey of Figure 20*a* began. After one revolution of the deferent, the epicycle will have turned slightly more than three times, and the planet will have arrived at position *P′*, so that it now appears to the west of its

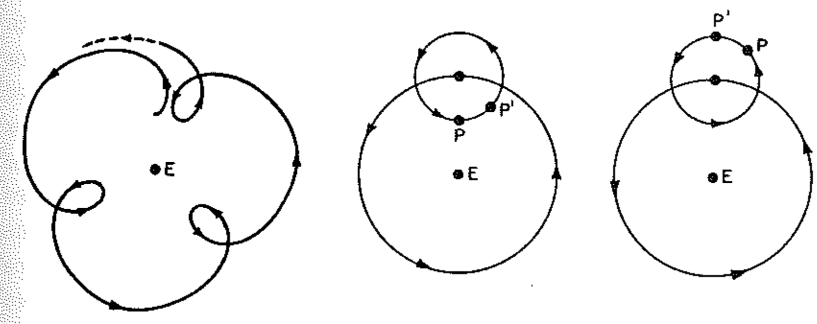

Figure 20. Motion generated by an epicycle and deferent when the epicycle turns slightly more than three times for each revolution of the deferent. The planet's path during a single complete journey through the stars is shown in (*a*). This journey requires more than one revolution of the deferent, as indicated by (*b*), which shows the planet's position at the beginning (*P*) and the end (*P′*) of the deferent's first full revolution. Diagram (*c*) shows the planet's position at the beginning and end of a later revolution of the deferent, one that carries the planet more than once around the ecliptic.

starting point. The deferent must turn eastward through more than a single revolution to carry the planet fully around the ecliptic; the corresponding trip through the constellations therefore requires more time than the average. Others, however, require less. After several more revolutions of the deferent, each ending with the planet still farther from the earth, the planet might start a new journey from the new position *P* in Figure 20*c*. One more revolution of the deferent would carry the planet to *P′*, a point to the east of *P* Since this revolution of the deferent carries the planet through more than one trip around the ecliptic, this journey is a particularly rapid one. Figures 20*b* and 20*c* represent very nearly the extreme values of the time required for a journey around the ecliptic; intermediate trips consume intermediate amounts of time; on the average, a journey around the ecliptic requires the same time as a rotation of the deferent. But the epicycle-deferent system allows for deviations from one trip to the next. Once again it provides an economical explanation of an observed irregularity of the planetary motions.

To describe the motions of all the planets a separate epicycle-deferent system must be designed for each. The motion of the sun and moon can be treated approximately by a deferent alone, for these planets do not retrogress. The sun's deferent turns once a year; the moon's revolves once in 27⅓ days. The epicycle-deferent system for Mercury is much like the one discussed above; the deferent turns once a year and the epicycle once in 116 days. By utilizing the observations recorded early in this chapter, we could design similar systems for other planets. Most of these would yield looped planetary paths like the one shown in Figure 20*a*. If the epicycle is larger relative to the deferent, the size of the loops is increased. If the epicycle turns more quickly relative to the speed of the deferent, then there are more loops included in one journey around the ecliptic. There are approximately eleven loops in each trip made by Jupiter, and approximately twenty-eight in each by Saturn. In short, by appropriate variations in the relative sizes and the speeds of the epicycle and the deferent, this system of compounded circular motions can be adjusted to fit approximately an immense variety of planetary motions. A properly designed combination of circles will even give a good qualitative account of the immense irregularities in the motion of an atypical planet like Venus (Figure 21).

Ptolemaic Astronomy

The discussion of the previous section illustrates the power and versatility of the epicycle-deferent system as a method for ordering and predicting the motions of the planets. But this is only the first step. Once the system was available to account for the most striking irregularities of planetary motion – retrogression and the irregular amounts of time consumed in successive journeys around the ecliptic – it became clear that there were still other, though very much smaller, irregularities to be considered.

Just as the two-sphere model provided a precise mechanism for the diurnal motions, thus permitting detailed study of the principal planetary irregularities, so the epicycle-deferent system, by providing

an account of the main planetary motions, permitted the observational isolation of smaller irregularities. This is the first example of the con-

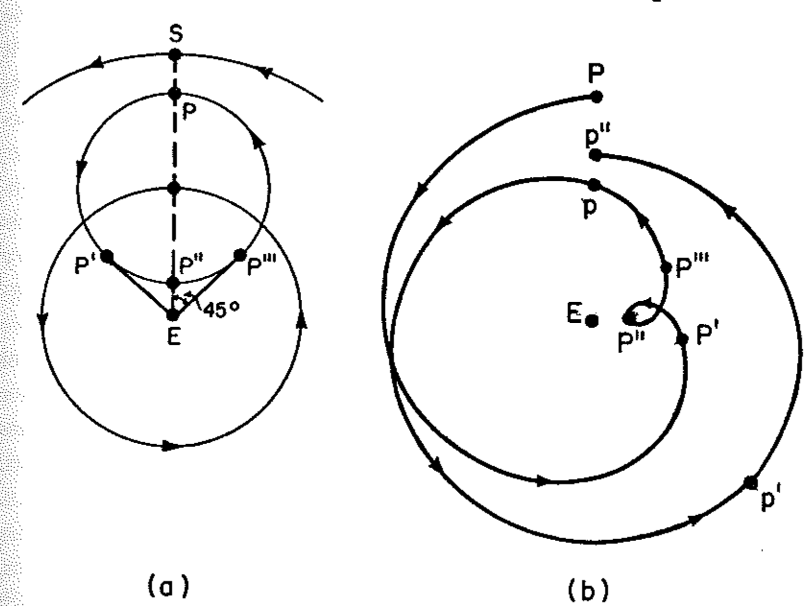

Figure 21. (*a*) A one-epicycle one-deferent system for Venus and (*b*) the motion that it generates in the plane of the ecliptic.

In (*a*), notice the following characteristics of the design: The deferent rotates once in a year, so that if the center of the epicycle is once aligned with the earth, *E*, and the center of the sun, *S*, it will stay in alignment forever, and Venus will never appear very far from the sun. The angles *SEP′* and *SEP‴* are the largest angles that can appear between the sun and Venus, and the condition that these angles of maximum elongation be 45° completely determines the relative sizes of the epicycle and deferent. The epicycle rotates once in 584 days, so that if Venus starts at *P*, close to the sun, it will arrive at *P′* (maximum elongation as an evening star) after 219 days (3/8 revolution); at *P″* after 292 days (1/2 revolution); and at *P‴* (maximum elongation as a morning star) after 365 days (5/8 revolution).

The second diagram shows the path along which Venus is carried by the moving circles sketched in (*a*). Here *P* is the starting point, as in the first diagram; *P′* is Venus's position at maximum eastward elongation (219 days); *P″* is the planet's location midway through a retrograde loop (292 days); and *P‴* is its position at maximum westward elongation (365 days). Venus's first journey around the ecliptic ends at *p* after 406 days (note the great length) and includes one retrogression and two maximum elongations. Its next trip (*p* to *p′* to *p″*) requires only 295 days and includes none of these characteristic phenomena. At *p′* Venus is again closest to the sun, a position reached after one complete revolution of the epicycle (584 days). This is, at least qualitatively, the way Venus does behave!

cept's fruitfulness. When the motion predicted by a one-epicycle one-deferent system is compared with the observed motion of an individual planet, it turns out that the planet *is* not always seen at quite the position on the ecliptic where the geometry of the model says it should be. Venus does not, if observed precisely, always attain its maximum deviation of 45° from the sun; the intervals between successive retrogressions of a single planet are not always quite the same; and none of the planets, except the sun, stays on the ecliptic throughout its motion. The one-epicycle one-deferent system was not, therefore, the final answer to the problem of the planets. It was only a very promising start and one that lent itself to both immediate and long-continued development. During the seventeen centuries that separate Hipparchus from Copernicus all the most creative practitioners of technical astronomy endeavored to invent some new set of minor geometric modifications that would make the basic one-epicycle one-deferent technique precisely fit the observed motion of the planets.

In antiquity the greatest of these attempts was made around A.D. 150 by the astronomer Ptolemy. Because his work displaced that of his predecessors and because all of his successors, including Copernicus, modelled their work upon his, the whole series of attempts for which Ptolemy provides the archetype is now usually known as Ptolemaic astronomy. That phrase, "Ptolemaic astronomy," refers to a traditional approach to the problem of the planets rather than to any one of the particular putative solutions suggested by Ptolemy himself, his predecessors, or his successors. Each of the particular individual solutions, and especially Ptolemy's, has an intense interest, both technical and historical, but both the particular solutions and their historical interrelationships are too complex to be considered here. Instead of attempting a general developmental account of the various Ptolemaic planetary systems, we shall therefore simply survey the main sorts of modification to which the basic epicycle-deferent system was subjected at various times between its first invention three centuries before Christ and its rejection by the followers of Copernicus.

Though their most important application is to the complex motions of the planets, the principal ancient and medieval modifications of the epicycle-deferent system are most simply described in their occasional applications to the apparently simpler motions of the sun and moon. The sun, for example, does not retrogress, so its motion does not require

a major epicycle of the sort described in the last section. But fixing the sun on a deferent that rotates uniformly about the earth as center does not give a quantitatively precise account of the solar motion, for, as shown by a reëxamination of the dates of the solstices and equinoxes listed in Chapter 1, the sun takes almost 6 days longer to move from the vernal equinox to the autumnal equinox (180° along the ecliptic) than it does to move back from the autumnal equinox to the vernal equinox (again 180°). The sun's motion along the ecliptic is slightly more rapid during the winter than summer, and such a motion cannot be produced by a fixed point on a uniformly rotating earth-centered circle. Examine Figure 22*a*, in which the earth is shown at the center of a uniformly rotating deferent circle and in which the positions of the vernal and autumnal equinoxes on the sphere of the stars are indicated by the dashes *VE* and *AE*. Uniform rotation of the deferent will carry the sun, *S*, from *VE* to *AE* in the same time that it takes to carry it back from *AE* to *VE*, and this corresponds only approximately with observation.

Suppose, however, that the sun is removed from the deferent and placed on a small epicycle that rotates once westward while the deferent rotates once eastward. Eight positions of the sun in such a system are shown in Figure 22*b*. It is clear that the summer half of the deferent's rotation does not carry the sun the entire distance from *VE* to *AE* and that the winter half of the rotation carries the sun farther than the distance from *AE* to *VE*. So the effect of the epicycle is to increase the time spent by the sun in the 180° between *VE* and *AE* and to decrease

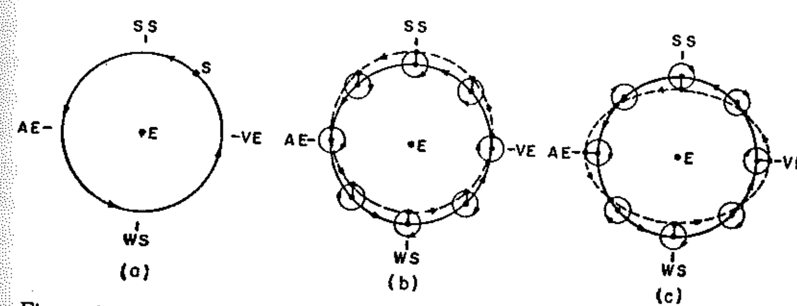

Figure 22. Functions of a minor epicycle. In (*a*) the sun, moved by a single earth-centered deferent, requires the same time to move from *AE* to *VE* that it needs to move back. In (*b*) the joint motion of deferent and minor epicycle carries the sun along the broken curve, so that more time is required for the trip from *VE* to *AE* than for the return. Diagram (*c*) shows the curve generated when the minor epicycle revolves at twice the rate used in constructing (*b*).

the time spent in the other half of the ecliptic between *AE* and *VE*. If the radius of the little epicycle is 0.03 the radius of the deferent, the difference in the time spent by the sun in the winter and the summer halves of the ecliptic will be the required 6 days.

The epicycle employed in the preceding discussion to correct a minor irregularity of the sun's motion is relatively small, and it produces no retrograde loops. Its function is therefore quite different from that of the larger epicycles considered in the last section, and, though Ptolemaic astronomers never did so, it will prove convenient to keep these two functions apart. Henceforth we shall use the term "major epicycle" for the large epicycles used to produce the qualitative appearance of retrograde motion and the term "minor epicycle" for the additional circles used to eliminate small quantitative discrepancies between theory and observation. All versions of the Ptolemaic system, both before and after Ptolemy, had just five major epicycles, and it is these with which Copernicus' reform did away. In contrast, the number of minor epicycles and similar devices needed to account for small quantitative discrepancies depended only on the precision of the available observations and on the accuracy of the predictions demanded from the system. The number of minor epicycles employed in the various versions of Ptolemaic astronomy therefore varied greatly from one version to the next. Systems employing half a dozen to a dozen minor epicycles were not uncommon in antiquity and the Renaissance, for by an appropriate choice of the size and speed of minor epicycles almost any sort of small irregularity could be explained away. That is why, as we shall see, Copernicus' astronomical system was so nearly as complex as Ptolemy's. Though his reform eliminated major epicycles, Copernicus was as dependent upon minor epicycles as his predecessors.

One sort of irregularity was treated with the aid of a minor epicycle in Figure 22*b*; another sort is shown in Figure 22*c*. There the minor epicycle rotates twice westward while the deferent moves once eastward. Combining the two rotations results in a total motion (broken line in the figure) along a flattened circle. A planet moving on this curve moves faster and spends less time in the vicinity of the summer and winter solstices than it does near the two equinoxes. If the epicycle had turned slightly less than twice while the deferent rotated once, then the positions on the ecliptic at which the planet's apparent speed was greatest would have changed on successive trips around the

ecliptic. If it had appeared fastest near the summer solstice on one trip, it would have passed the summer solstice before gaining its greatest speed on the next trip. Other variations of this sort can be produced at will.

Uses of the minor epicycle are not limited to the nonretrogressing planets, the sun and moon. A minor epicycle can be placed upon a major epicycle and used in the prediction of the more elaborate planetary motions; in fact, planetary motions provided the minor epicycle's main astronomical application. One such application, an epicycle on an epicycle on a deferent, is shown in Figure 23*a*. If the major epicycle turns eight times eastward and the minor epicycle once westward during one rotation of the deferent, then the path within the sphere of the stars described by the planet is that shown in Figure 23*b*. It has eight normal retrograde loops, but these are somewhat more densely clustered in the half of the ecliptic between the vernal equinox and the autumnal equinox than in the half between the autumnal and vernal equinox. If the rate of rotation of the minor epicycle is now

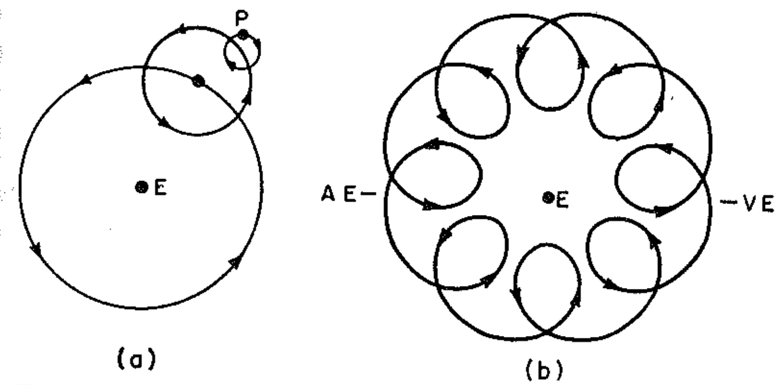

Figure 23. An epicycle on an epicycle on a deferent (*a*) and a typical path through space (*b*) generated by this system of compounded circles. For simplicity, the path has been shown rejoining itself smoothly, a situation that does not occur in the motion of real planets.

doubled, the path described by the planet is flattened as in Figure 22*c*. These diagrams begin to suggest the complexities of the paths that minor epicycles can produce.

Nor is a minor epicycle the only device available for correcting minor discrepancies between one-epicycle one-deferent systems and the observed behavior of the planets. A glance at Figure 22*b* indicates that the effect there produced by a minor epicycle that rotates westward once as the deferent turns through a single eastward rotation can equally well be achieved by a single deferent whose center is displaced from the center of the earth. Such a displaced circle, known to ancient astronomers as an eccentric, is shown in Figure 24*a*. If the distance

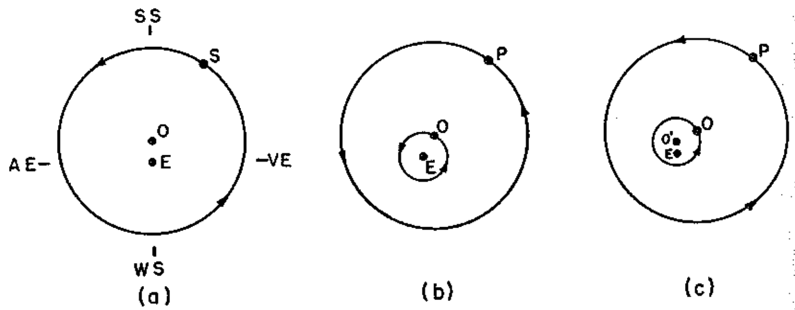

Figure 24. An eccentric (*a*), an eccentric on a deferent (*b*), and an eccentric on an eccentric (*c*).

between the earth, *E*, and the center of the eccentric, *O*, is about 0.03 the radius of the eccentric, this displaced circle will account for the 6 extra days that the sun spends between the vernal and autumnal equinoxes. That is the particular device that Ptolemy used in his own account of the sun. Other values of the distance *EO*, employed in conjunction with one or more epicycles, will account for other minor planetary irregularities. Additional effects may be obtained by placing the center of the eccentric on a small deferent (Figure 24*b*), or on a second smaller eccentric (Figure 24*c*). These two devices can be shown to be geometrically fully equivalent to a minor epicycle on a deferent and a minor epicycle on an eccentric, respectively, and most Ptolemaic astronomers used these small central circles in preference to minor epicycles. In all cases one or more epicycles may be added, and any or all of these circles may be tilted into different planes to account for the north and south deviations of the planets from the ecliptic.

One more device, the equant, was developed in antiquity to aid in the reconciliation of the theory of epicycles with the results of accurate observation. This device is of particular importance because Copernicus' aesthetic objections to it (Chapter 5) provided one essential

motive for his rejection of the Ptolemaic system and his search for a radically new method of computation. Copernicus used epicycles and eccentrics like those employed by his ancient predecessors, but he did not use equants, and he felt that their absence from his system was one of its greatest advantages and one of the most forceful arguments for its truth.

One form of equant, designed, for simplicity of illustration, to account for the previously discussed irregularity in the sun's motion, is shown in Figure 25. The center of the sun's deferent coincides as before with the center of the earth, *E*, but the deferent's rate of rotation is now required to be uniform not with respect to its geometric center *E*, but with respect to an equant point, *A*, displaced in this case toward the summer solstice. That is, the angle *a* subtended at the equant point *A* by the sun and the summer solstice is required to change at a constant rate. If the angle increases by 30° in one month, then it must increase by 30° in every month of the same length. In the figure the sun is shown at the vernal equinox, *VE*. To reach the autumnal equinox, *AE*, it must complete a semicircle, which will change the angle *a* by more than 180°, and to return from *AE* to *VE* it must complete a second semicircle, which will change *a* by less than 180°. Since every 180° increase in *a* requires the same amount of time, the sun must take longer to go from *VE* to *AE* than it requires for the return journey from *AE* to *VE*. Therefore, viewed from the equant point *A*, the sun travels at an irregular rate, fastest near the winter solstice and slowest near the summer solstice.

That is the defining feature of the equant. The rate of rotation of a deferent or some other planetary circle is required to be uniform, not with respect to its own geometric center, but with respect to an equant point displaced from that center. Observed from the geometric center of its deferent, the planet seems to move at an irregular rate or to wobble. Because of the wobble, Copernicus felt that the equant was not a legitimate device for application to astronomy. For him the apparent irregularities of the rotation were violations of the uniform circular symmetry that made the system of epicycles, deferents, and eccentrics so plausible and attractive. Since the equant was normally applied to eccentrics and since similar devices occasionally made the epicycle wobble as well, it is not hard to imagine how Copernicus might have considered this aspect of Ptolemaic astronomy monstrous.

The mathematical devices sketched in the preceding pages were not all developed at a stroke or by Ptolemy. Apollonius, in the third century B.C., knew both major epicycles (Figure 19*a*) and eccentrics with moving centers (Figure 24*b*). During the following century Hipparchus added minor epicycles and a more general theory of eccentrics to the arsenal of astronomical weapons. In addition he combined these devices to provide the first quantitatively adequate account of the irregularities in the motions of the sun and moon. Ptolemy himself added the equant, and during the thirteen centuries between his time and that of Copernicus, first Moslem and then European astronomers employed still other combinations of circles – including the epicycle on an epicycle (Figure 23*a*) and the eccentric on an eccentric (Figure 24*c*) – to account for additional planetary irregularities.

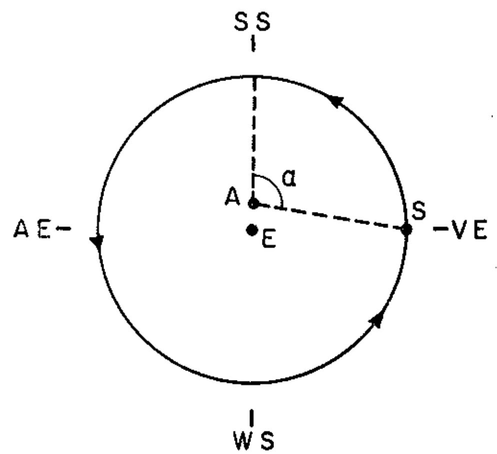

Figure 25. The equant. The sun, S, moves on the earth-centered circle but at an irregular rate determined by the condition that the angle *a* vary uniformly with time.

But Ptolemy's contribution is the outstanding one, and this entire technique of resolving the problem of the planets is appropriately known by his name, because it was Ptolemy who first put together a particular set of compounded circles to account, not merely for the motions of the sun and moon, but for the observed quantitative regularities and irregularities in the apparent motions of all the seven planets. His *Almagest*, the book that epitomizes the greatest achievements of ancient astronomy, was the first systematic mathematical treatise to give a *complete, detailed,* and *quantitative* account of all the celestial motions. Its results were so good and its methods so powerful that after Ptolemy's death the problem of the planets took a new form. To increase the accuracy or simplicity of planetary theory Ptolemy's successors added epicycles to epicycles and eccentrics to eccentrics, exploiting all the immense versatility of the fundamental Ptolemaic technique. But they seldom or never sought fundamental modifications of that technique. The problem of the planets had become simply a problem of design, a problem to be attacked principally by the re-arrangement of existing elements. What particular combination of deferents, eccentrics, equants, and epicycles would account for the planetary motions with the greatest simplicity and precision?

We cannot pursue further the individual quantitative solutions of this problem proposed by Hipparchus, Ptolemy, and their successors. The complete quantitative systems are mathematically too complex. Much of Ptolemy's *Almagest* consists of quantitative mathematical tables, diagrams, formulas, and proofs, of long illustrative computations, and of lists of numerous observations. Yet the problems that set Copernicus to searching for a new approach to the problem of the planets and the advantages that he claimed to derive from his new system all lie within this abstruse body of quantitative theory. Copernicus did not attack the two-sphere universe, though his work ultimately overthrew it, and he did not abandon the use of epicycles and eccentrics, though these too were abandoned by his successors. What Copernicus did attack and what started the revolution in astronomy was certain of the apparently trivial mathematical details, like equants, embodied in the complex mathematical systems of Ptolemy and his successors. The initial battle between Copernicus and the astronomers of antiquity was fought over technical minutiae like those sketched in this section.

The Anatomy of Scientific Belief

For its subtlety, flexibility, complexity, and power the epicycle-deferent technique sketched in the two preceding sections has no parallel in the history of science until quite recent times. In its most developed form the system of compounded circles was an astounding achievement. *But it never quite worked.* Apollonius' initial conception solved the primary planetary irregularities – retrograde motion, variation of brightness, alteration in the time required for successive journeys around the ecliptic — and it did so simply and at a stroke. But it also disclosed some residual secondary irregularities. Some of these were explained away by the more elaborate system of compounded circles developed by Hipparchus, but still the theory did not quite match the results of observation. Even Ptolemy's complex combination of deferents, eccentrics, epicycles, and equants did not precisely reconcile theory and observation, and Ptolemy's was neither the most complex nor the last version of the system. Ptolemy's many successors, first in the Moslem world and then in medieval Europe, took up the problem where he had left it and sought in vain for the solution that had evaded him. Copernicus was still grappling with the same problem.

There are many variations of the Ptolemaic system besides the one that Ptolemy himself embodied in the *Almagest*, and some of them achieved considerable accuracy in predicting planetary positions. But the accuracy was invariably achieved at the price of complexity — the addition of new minor epicycles or equivalent devices — and increased complexity gave only a better approximation to planetary motion, not finality. No version of the system ever quite withstood the test of additional refined observations, and this failure, combined with the total disappearance of the conceptual economy that had made cruder versions of the two-sphere universe so convincing, ultimately led to the Copernican Revolution.

But the Revolution was an incredibly long time coming. For almost 1800 years, from the time of Apollonius and Hipparchus until the birth of Copernicus, the conception of compounded circular orbits within an earth-centered universe dominated every technically developed attack upon the problem of the planets, and there were a great many such attacks before Copernicus'. Despite its slight but recognized inaccuracy and its striking lack of economy (contrast the earlier two-sphere universe described in Chapter 1), the developed Ptolemaic system had an immense life span, and the longevity of this magnificent but clearly imperfect system poses a pair of closely related puzzles: How did the two-sphere universe and the associated epicycle-deferent planetary theory gain so tight a grip upon the imagination of the astronomers? And, once gained, how was the psychological grip of this traditional approach to a traditional problem released? Or to put the same questions more directly: Why was the Copernican Revolution so delayed? And how did it come to pass at all?

These are questions about the history of a particular set of ideas, and as history they will be considered at some length below. But they are also more generally concerned with the nature and structure of conceptual schemes and with the process by which one conceptual scheme replaces another. It is therefore illuminating to approach them first by returning briefly to the abstract logical and psychological categories introduced in the penultimate section of the first chapter. We there examined the functions of a conceptual scheme: we now ask how a smoothly functioning scheme, like the early two-sphere universe, can be replaced. Examine the logic of the phenomenon first.

Logically there are always many alternative conceptual schemes capable of bringing order to any *prescribed* list of observations, but these alternatives differ in their predictions about phenomena not included on the list. Both the Copernican and the Newtonian systems will account for naked-eye stellar and solar observations just as adequately as will the two-sphere system; Heraclides' system will do the same and so will the system developed by Copernicus' successor, Tycho Brahe; in theory there are an infinite number of other alternatives besides. But these alternatives agree principally about observations that have already been made. They do not give identical accounts of all possible observations. The Copernican system, for example, differs from the two-sphere universe in predicting an apparent annual motion of the stars, in demanding a much larger diameter for the stellar sphere, and in suggesting (though not to Copernicus) a new sort of solution for the problem of the planets. It is because of differences like these (and there are many others besides) that a scientist must believe in his system before he will trust it as a guide to fruitful investigations of the *unknown*. Only one of the different alternatives can *conceivably* represent reality, and the scientist exploring new territory must feel confident that he has chosen that one or the closest of the available approximations to it. But the scientist pays a price for this commitment to a particular alternative: he may make mistakes. A single observation incompatible with his theory demonstrates that he has been employing the wrong theory all along. His conceptual scheme must then be abandoned and replaced.

That, in outline, is the logical structure of a scientific revolution. A conceptual scheme, believed because it is economical, fruitful, and cosmologically satisfying, finally leads to results that are incompatible with observation; belief must then be surrendered and a new theory adopted; after this the process starts again. It is a useful outline, because the incompatibility of theory and observation is the ultimate source of every revolution in the sciences. But historically the process of revolution is never, and could not possibly be, so simple as the logical outline indicates. As we have already begun to discover, observation is never *absolutely* incompatible with a conceptual scheme.

To Copernicus the behavior of the planets was incompatible with the two-sphere universe; he felt that in adding more and more circles his predecessors had simply been patching and stretching the Ptolemaic system to force its conformity with observations; and he believed that the very necessity for such patching and stretching was clear evidence that a radically new approach was imperatively required. But Copernicus' predecessors, to whom exactly the same sorts of instruments and observations were available, had evaluated the same situation quite differently. What to Copernicus was stretching and patching was to them a natural process of adaptation and extension, much like the process which at an earlier date had been employed to incorporate the motion of the sun into a two-sphere universe designed initially for the earth and stars. Copernicus' predecessors had little doubt that the system would ultimately be made to work.

In short, though scientists undoubtedly do abandon a conceptual scheme when it seems in irreconcilable conflict with observation, the emphasis on logical incompatibility disguises an essential problem. What is it that transforms an apparently temporary discrepancy into an inescapable conflict? How can a conceptual scheme that one generation admiringly describes as subtle, flexible, and complex become for a later generation merely obscure, ambiguous, and cumbersome? Why do scientists hold to theories despite discrepancies, and, having held to them, why do they give them up? These are problems in the anatomy of scientific belief. They are the primary concern of the next two chapters, which set the stage for the Copernican Revolution proper.

Our immediate problem, however, is the analysis of the grip exerted upon men's minds by the ancient tradition of astronomical research. How could this tradition provide a set of mental grooves that guided the astronomical imagination, limited the conceptions available in research, and made certain sorts of innovations difficult to conceive and more difficult to accept? We have already dealt, at least implicitly, with the strictly astronomical aspects of this problem. Both the two-sphere universe and the associated epicycle-deferent technique were initially highly economical and fruitful; their first successes seemed to guarantee the fundamental soundness of the approach; surely only minor modifications would be required to make the mathematical predictions correspond with observation. A conviction of this sort is difficult to break, particularly once it has been embodied in the practice of a whole generation of astronomers who transmit it to their successors through their teaching and writing. This is the band-wagon effect in the realm of scientific ideas.

The band-wagon effect is not, however, the whole explanation of the strength of the astronomical tradition, and in trying to complete the explanation we shall be temporarily led away from astronomical problems altogether. The two-sphere universe provided a fruitful guide to the solution of problems outside as well as inside astronomy. By the end of the fourth century B.C. it had been applied not only to the problem of the planets, but also to terrestrial problems, like the fall of a leaf and the flight of an arrow, and to spiritual problems, like the relation of man to his gods. If the two-sphere universe, and particularly the conception of a central and stable earth, then seemed the indubitable starting point of all astronomical research, this was primarily because the astronomer could no longer upset the two-sphere universe without overturning physics and religion as well. Fundamental astronomical concepts had become strands in a far larger fabric of thought, and the nonastronomical strands could be as important as the astronomical in binding the imagination of astronomers. The story of the Copernican Revolution is not, therefore, simply a story of astronomers and the skies.

5

COPERNICUS' INNOVATION

Copernicus and the Revolution

The publication of Copernicus' *De Revolutionibus Orbium Caelestium* in 1543 inaugurates the upheaval in astronomical and cosmological thought that we call the Copernican Revolution. To this point we have dealt only with the background of that Revolution, setting the stage upon which the Revolution occurred. Now we turn to the Revolution itself, dealing first, in this chapter, with Copernicus' contributions to it. So far as possible we shall discover those contributions in Copernicus' own words, drawn from the *De Revolutionibus*, the book that presented the new astronomy to the world. Almost immediately we shall encounter difficulties and incongruities upon whose resolution depends our understanding of the Copernican Revolution or, since that Revolution is in many respects typical, of any other major conceptual upheaval in the sciences.

The *De Revolutionibus* is for us a problem text. Some of its problems derive simply from the intrinsic difficulties of its subject matter. All but the introductory First Book is too mathematical to be read with understanding by anyone except a technically proficient astronomer. We must deal with its essential technical contributions in relatively nonmathematical paraphrase, much like that employed in treating the *Almagest*, and we shall by-pass in this process certain of the essential problems that the *De Revolutionibus* presented to its sixteenth-century readers. Had Copernicus propounded the new astronomy in the simplified form to which we shall frequently resort in this chapter, its reception might have been quite different. Opposition to a more comprehensible work might, for example, have been marshaled sooner. Our first problem is therefore the barrier which a lack of technical proficiency places between us and the central books of the work that inaugurated the Revolution.

But the technical obscurity of the *De Revolutionibus*, though it must be recognized at the start, is neither the most difficult nor the most important sort of problem inherent in Copernicus' work. The principal difficulties of the *De Revolutionibus* and the ones that we may not evade arise rather from the apparent incompatibility between that text and its role in the development of astronomy. In its consequences the *De Revolutionibus* is undoubtedly a revolutionary work. From it derive a fundamentally new approach to planetary astronomy, the first accurate and simple solution of the problem of the planets, and ultimately, with other fibers added to the pattern, a new cosmology. But, to any reader aware of this outcome, the *De Revolutionibus* itself must be a constant puzzle and paradox, for, measured in terms of its consequences, it is a relatively staid, sober, and unrevolutionary work. Most of the essential elements by which we know the Copernican Revolution – easy and accurate computations of planetary position, the abolition of epicycles and eccentrics, the dissolution of the spheres, the sun a star, the infinite expansion of the universe – these and many others are not to be found anywhere in Copernicus' work. In every respect except the earth's motion the *De Revolutionibus* seems more closely akin to the works of ancient and medieval astronomers and cosmologists than to the writings of the succeeding generations who based their work upon Copernicus' and who made explicit the radical consequences that even its author had not seen in his work.

The significance of the *De Revolutionibus* lies, then, less in what it says itself than in what it caused others to say. The book gave rise to a revolution that it had scarcely enunciated. It is a revolution-making rather than a revolutionary text. Such texts are a relatively frequent and extremely significant phenomenon in the development of scientific thought. They may be described as texts that shift the direction in which scientific thought develops; a revolution-making work is at once the culmination of a past tradition and the source of a novel future tradition. As a whole the *De Revolutionibus* stands almost entirely within an ancient astronomical and cosmological tradition; yet within its generally classical framework are to be found a few novelties which shifted the direction of scientific thought in ways unforeseen by its author and which gave rise to a rapid and complete break with the ancient tradition. Viewed in a perspective provided by the history of astronomy, the *De Revolutionibus* has a dual nature. It is at once ancient and modern, conservative and radical. Therefore its significance can be discovered only by looking simultaneously to its past and to its future, to the tradition from which it derived and to the tradition which derives from it.

That double view of a single work is the principal problem of this chapter. What is the relation of Copernicus to the ancient astronomical tradition within which he was educated? More precisely, what aspects of that tradition led him to believe that some astronomical innovation was essential, that certain aspects of ancient cosmology and astronomy must be rejected? And, having resolved to break with an old tradition, to what extent was he still necessarily bound by it as the only source of those intellectual and observational tools required for the practice of astronomy? Again, what is Copernicus' relation to the tradition of modern planetary astronomy and cosmology? Given the limitations imposed by the training and tools of classical astronomy, what creative innovations could his work contain? How could those innovations, which ultimately produced a radically new astronomy and cosmology, be embedded initially in a predominantly classical frame? And how could those novelties be recognized and adopted by his successors? These problems and their corollaries are symptomatic of the real difficulties of the *De Revolutionibus* or of any scientific work which, though born within one tradition of scientific thought, is the source of a new tradition that ultimately destroys its parent.

Motives for Innovation — Copernicus' Preface

Copernicus is among that small group of Europeans who first revived the full Hellenistic tradition of technical mathematical astronomy which in antiquity had culminated in the work of Ptolemy. The *De Revolutionibus* was modeled on the *Almagest*, and it was directed almost exclusively to that small group of contemporary astronomers equipped to read Ptolemy's treatise. With Copernicus we return for the first time to the sort of technical astronomical problem with which we last dealt in Chapter 3 when examining the developed Ptolemaic system. In fact we return to the same problem. The *De Revolutionibus* was written to solve the problem of the planets, which, Copernicus felt, Ptolemy and his successors had left unsolved. In

Copernicus' work the revolutionary conception of the earth's motion is initially an anomalous by-product of a proficient and devoted astronomer's attempt to reform the techniques employed in computing planetary position. That is the first significant incongruity of the *De Revolutionibus*, the disproportion between the objective that motivated Copernicus' innovation and the innovation itself. It can be discovered almost at the start of the prefatory letter that Copernicus prefixed to the *De Revolutionibus* in order to sketch the motive, the source, and the nature of his scientific achievement.[1]

TO THE MOST HOLY LORD, POPE PAUL III

The Preface of Nicholas Copernicus to the Books of the Revolutions

I may well presume, most Holy Father, that certain people, as soon as they hear that in this book about the Revolutions of the Spheres of the Universe I ascribe movement to the earthly globe, will cry out that, holding such views, I should at once be hissed off the stage. For I am not so pleased with my own work that I should fail duly to weigh the judgment which others may pass thereon; and though I know that the speculations of a philosopher are far removed from the judgment of the multitude – for his aim is to seek truth in all things as far as God has permitted human reason so to do – yet I hold that opinions which are quite erroneous should be avoided.

Thinking therefore within myself that to ascribe movement to the Earth must indeed seem an absurd performance on my part to those who know that many centuries have consented to the establishment of the contrary judgment, namely that the Earth is placed immovably as the central point in the middle of the Universe, I hesitated long whether, on the one hand, I should give to the light these my Commentaries written to prove the Earth's motion, or whether, on the other hand, it were better to follow the example of the Pythagoreans and others who were wont to impart their philosophic mysteries only to intimates and friends, and then not in writing but by word of mouth, as the letter of Lysis to Hipparchus witnesses. [This letter, which Copernicus had at one time intended to include in the *De Revolutionibus*, describes the Pythagorean and Neoplatonic injunction against revealing nature's secrets to those who are not initiates of a mystical cult. Reference to it here exemplifies Copernicus' participation in the Renaissance revival of Neoplatonism discussed in the last chapter.] In my judgment they did so not, as some would have it, through jealousy of sharing their doctrines, but as fearing lest these so noble and hardly won discoveries of the learned should be despised by such as either care not to study aught save for gain, or – if by the encouragement and example of others they are stimulated to philosophic liberal pursuits – yet by reason of the dullness of their wits are in the company of philosophers as drones among bees. Reflecting thus, the thought of the scorn which I had to fear on account of the novelty and incongruity of my theory, well-nigh induced me to abandon my project.

These misgivings and actual protests have been overcome by my friends . . . [one of whom] often urged and even importuned me to publish this work which I had kept in store not for nine years only, but to a fourth period of nine years. . . . They urged that I should not, on account of my fears, refuse any longer to contribute the fruits of my labors to the common advantage of those interested in mathematics. They insisted that, though my theory of the Earth's movement might at first seem strange, yet it would appear admirable and acceptable when the publication of my elucidatory comments should dispel the mists of paradox. Yielding then to their persuasion I at last permitted my friends to publish that work which they have so long demanded.

That I allow the publication of these my studies may surprise your Holiness the less in that, having been at such travail to attain them, I had already not scrupled to commit to writing my thoughts upon the motion of the Earth. [Some years before the publication of the *De Revolutionibus* Copernicus had circulated among his friends a short manuscript called the *Commentariolus*, describing an earlier version of his sun-centered astronomy. A second advance report of Copernicus' major work, the *Narratio Prima* by Copernicus' student, Rheticus, had appeared in 1540 and again in 1541.] How I came to dare to conceive such motion of the Earth, contrary to the received opinion of the Mathematicians and indeed contrary to the impression of the senses, is what your Holiness will rather expect to hear. So I should like your Holiness to know that I was induced to think of a method of computing the motions of the spheres by nothing else than the knowledge that the Mathematicians are inconsistent in these investigations.

For, first, the mathematicians are so unsure of the movements of the Sun and Moon that they cannot even explain or observe the constant length of the seasonal year. Secondly, in determining the motions of these and of the other five planets, they use neither the same principles and hypotheses nor the same demonstrations of the apparent motions and revolutions. So some use only homocentric circles [the Aristotelian system, derived by Aristotle from Eudoxus and Callippus, and revived in Europe shortly before Copernicus' death by the Italian astronomers Fracastoro and Amici], while others [employ] eccentrics and epicycles. Yet even by these means they do not completely attain their ends. Those who have relied on homocentrics, though they have proven that some different motions can be compounded therefrom, have not thereby been able fully to establish a system which agrees with the phenomena. Those again who have devised eccentric systems, though they appear to have well-nigh established the seeming motions by calculations agreeable to their assumptions, have yet made many admissions [like the use of the equant] which seem to violate the first principle of uniformity in motion. Nor have they been able thereby to discern or deduce the principal thing – namely the shape of the Universe and the unchangeable symmetry of its parts. With them it is as though an artist were to gather the hands, feet, head and other members for his images from diverse models, each part excellently drawn, but not related to a single body, and since they in no way match each other, the result would be monster rather than man. So in the course of their exposition, which the mathematicians call their system, . . . we find that they have either omitted some indispensable detail or introduced something foreign and wholly irrelevant. This would of a surety not have been so had they followed fixed principles; for if their hypotheses were not misleading, all inferences based thereon might be surely verified. Though my present assertions are obscure, they will be made clear in due course.

An honest appraisal of contemporary astronomy, says Copernicus, shows that the earth-centered approach to the problem of the planets is hopeless. The traditional techniques of Ptolemaic astronomy have not and will not solve that problem; instead they have produced a monster; there must, he concludes, be a fundamental error in the basic concepts of traditional planetary astronomy. For the first time a technically competent astronomer had rejected the time-honored scientific tradition for reasons internal to his science, and this professional awareness of technical fallacy inaugurated the Copernican Revolution. A felt necessity was the mother of Copernicus' invention. But the feeling of necessity was a new one. The astronomical tradition had not previously seemed monstrous. By Copernicus' time a metamorphosis had occurred, and Copernicus' preface brilliantly describes the felt causes of that transformation.

Copernicus and his contemporaries inherited not only the *Almagest* but also the astronomies of many Islamic and a few European astronomers who had criticized and modified Ptolemy's system. These are the men to whom Copernicus refers as "the mathematicians." One had added or subtracted a few small circles; another had employed an epicycle to account for a planetary irregularity that Ptolemy had originally treated with an eccentric; still another had invented a means unknown to Ptolemy of accounting for small deviations from the motion predicted by a one-epicycle one-deferent system; others had, with new measurements, altered the rates at which the compounded circles of Ptolemy's system rotated. There was no longer one Ptolemaic system, but a dozen or more, and the number was multiplying rapidly with the multiplication of technically proficient astronomers. All these systems were modeled on the system of the *Almagest*, and all were therefore "Ptolemaic." But because there were so many variant systems, the adjective "Ptolemaic" had lost much of its meaning. The astronomical tradition had become diffuse; it no longer fully specified the techniques that an astronomer might employ in computing planetary position, and it could not therefore specify the results that he would obtain from his computations. Equivocations like these deprived the astronomical tradition of its principal source of internal strength.

Copernicus' monster has other faces. None of the "Ptolemaic" systems which Copernicus knew gave results that quite coincided with good naked-eye observations. They were no worse than Ptolemy's results, but they were also no better. After thirteen centuries of fruitless research a perceptive astronomer might well wonder, as Ptolemy could not have, whether further attempts within the same tradition could conceivably be successful. Besides, the centuries that had intervened between Ptolemy and Copernicus had magnified the errors of the traditional approach, thus providing an additional source of discontent. The motions of a system of epicycles and deferents are not unlike those of the hands of a clock, and the apparent error of a clock increases with the passage of time. If a clock loses, say, 1 second per decade, its error may not be apparent at the end of a year or the end of ten. But the error can scarcely be evaded after a millenium, when it will have increased to almost 2 minutes. Since Copernicus and his contemporaries possessed astronomical data extending over a time span thirteen centuries longer than that covered by Ptolemy's data, they could impose a far more sensitive check upon their systems. They were necessarily more aware of the errors inherent in the ancient approach.

The passage of time also presented the sixteenth-century astronomer with a counterfeit problem which ironically was even more effective than the real motion of the planets in fostering recognition of the errors in the Ptolemaic method. Many of the data inherited by Copernicus and his colleagues were bad data which placed the planets and stars in positions that they had never occupied. Some of the erroneous records had been collected by poor observers; others had once been based upon good observations but had been miscopied or misconstrued during the process of transmission. No simple planetary system – Ptolemy's, Copernicus', Kepler's, or Newton's – could have reduced to order the data that Renaissance astronomers thought they had to explain. The complexity of the problem presented by Renaissance data transcended that of the heavens themselves. Copernicus was himself a victim of the data that had originally aided him in rejecting the Ptolemaic system. His own system would have given far better results if he had been as skeptical about his predecessors' observations as he was about their mathematical systems.

Diffuseness and continued inaccuracy – these are the two principal characteristics of the monster described by Copernicus. In so far as the Copernican Revolution depended upon explicit changes within the astronomical tradition itself, these are its major sources. But they are not the only ones. We may also ask why Copernicus was able to recognize the monster. Some of the tradition's apparent metamorphosis must have been in the eye of the beholder, for the tradition had been diffuse and inaccurate before. In fact we have already considered this question. Copernicus' awareness of monstrosity depended upon that larger climate of philosophical and scientific opinion whose genesis and nature were described in the last chapter. From the state of contemporary astronomy a man without Copernicus' Neoplatonic bias might have concluded merely that the problem of the planets could have no solution that was simultaneously simple and precise. Similarly, an astronomer unacquainted with the tradition of scholastic criticism might have been unable to develop parallel criticisms for his own field. These and other novelties developed in the last chapter are main currents of Copernicus' time. Though he seems unaware of them, Copernicus was carried by these philosophical currents, as his contemporaries were unwittingly carried by the motion of the earth. Copernicus' work remains incomprehensible unless viewed in its relation to both the internal state of astronomy and the larger intellectual climate of the age. Both together produced the monster.

Discontent with a recognized monster was, however, only the first step toward the Copernican Revolution. Next came a search whose beginnings are described in the remaining portions of Copernicus' prefatory letter:

> I pondered long upon this uncertainty of mathematical tradition in establishing the motions of the system of the spheres. At last I began to chafe

that philosophers could by no means agree on any one certain theory of the mechanism of the Universe, wrought for us by a supremely good and orderly Creator, though in other respects they investigated with meticulous care the minutest points relating to its circles. [Note how Copernicus equates "orderly" with "mathematically neat," an aspect of his Neoplatonism from which any good Aristotelian would have vehemently dissented. There are other sorts of orderliness.] 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 Hicetas [of Syracuse, fifth century B.C.] 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 rest hold the Earth to be stationary, but Philolaus the Pythagorean [fifth century B.C.] says that she moves around the [central] fire on an oblique circle like the Sun and Moon. Heraclides of Pontus and Ecphantus the Pythagorean [fourth century B.C.] also make the Earth to move, not indeed through space but by rotating round her own center 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 so be discovered.

Thus assuming motions, which in my work I ascribe to the Earth, by long and frequent observations I have at last discovered that, if the motions of the rest of the planets be brought into relation with the circulation of the Earth and be reckoned in proportion to the circles of each planet, not only do their phenomena presently ensue, but the orders and magnitudes of all stars and spheres, nay the heavens themselves, become so bound together that nothing in any part thereof could be moved from its place without producing confusion of all the other parts and of the Universe as a whole. . . . [Copernicus here points to the single most striking difference between his system and Ptolemy's. In the Copernican system it is no longer possible to shrink or expand the orbit of any one planet at will, holding the others fixed. Observation for the first time can determine the order and the relative dimensions of all the planetary orbits without resort to the hypothesis of space-filling spheres. We shall discuss the point more fully when we compare Copernicus' system with Ptolemy's.]

I doubt not that gifted and learned mathematicians will agree with me if they are willing to comprehend and appreciate, not superficially but thoroughly, according to the demands of this science, such reasoning as I

bring to bear in support of my judgment. But that learned and unlearned alike may see that I shrink not from any man's criticism, it is to your Holiness rather than anyone else that I have chosen to dedicate these studies of mine, since in this remote corner of Earth in which I live you are regarded as the most eminent by virtue alike of the dignity of your Office and of your love of letters and science. You by your influence and judgment can readily hold the slanderers from biting, though the proverb hath it that there is no remedy against a sycophant's tooth. It may fall out, too, that idle babblers, ignorant of mathematics, may claim a right to pronounce a judgment on my work, by reason of a certain passage of Scripture basely twisted to suit their purpose. Should any such venture to criticize and carp at my project, I make no account of them; I consider their judgment rash, and utterly despise it. I well know that even Lactantius, a writer in other ways distinguished but in no sense a mathematician, discourses in a most childish fashion touching the shape of the Earth, ridiculing even those who have stated the Earth to be a sphere. Thus my supporters need not be amazed if some people of like sort ridicule me too.

Mathematics are for mathematicians, and they, if I be not wholly deceived, will hold that these my labors contribute somewhat even to the Commonwealth of the Church, of which your Holiness is now Prince. For not long since, under Leo X, the question of correcting the ecclesiastical calendar was debated in the Council of the Lateran. It was left undecided for the sole cause that the lengths of the years and months and the motions of the Sun and Moon were not held to have been yet determined with sufficient exactness. From that time on I have given thought to their more accurate observation, by the advice of that eminent man Paul, Lord Bishop of Sempronia, sometime in charge of that business of the calendar. What results I have achieved therein, I leave to the judgment of learned mathematicians and of your Holiness in particular. And now, not to seem to promise your Holiness more than I can perform with regard to the usefulness of the work, I pass to my appointed task.

"Mathematics are for mathematicians." There is the first essential incongruity of the *De Revolutionibus*. Though few aspects of Western thought were long unaffected by the consequences of Copernicus' work, that work itself was narrowly technical and professional. It was mathematical planetary astronomy, not cosmology or philosophy, that Copernicus found monstrous, and it was the reform of mathematical astronomy that alone compelled him to move the earth. If his contemporaries were to follow him, they would have to learn to understand his detailed mathematical arguments about planetary position, and they would have to take these abstruse arguments more seriously than the first evidence of their senses. The Copernican Revolution was not primarily a revolution in the mathematical techniques employed to compute planetary position, but it began as one. In recognizing the need for and in developing these new techniques, Copernicus made his single original contribution to the Revolution that bears his name.

Copernicus was not the first to suggest the earth's motion, and he did not claim to have rediscovered the idea for himself. In his preface he cites most of the ancient authorities who had argued that the earth was in motion. In an earlier manuscript he even refers to Aristarchus, whose sun-centered universe very closely resembles his own. Although he fails, as was customary during the Renaissance, to mention his more immediate predecessors who had believed that the earth was or could be in motion, he must have known some of their work. He may not, for example, have known of Oresme's contributions, but he had probably at least heard of the very influential treatise in which the fifteenth-century Cardinal, Nicholas of Cusa, derived the motion of the earth from the plurality of worlds in an unbounded Neoplatonic universe. The earth's motion had never been a popular concept, but by the sixteenth century it was scarcely unprecedented. What was unprecedented was the mathematical system that Copernicus built upon the earth's motion. With the possible exception of Aristarchus, Copernicus was the first to realize that the earth's motion might solve an existing astronomical problem or indeed a scientific problem of any sort. Even including Aristarchus, he was the first to develop a detailed account of the astronomical consequences of the earth's motion. Copernicus' mathematics distinguish him from his predecessors, and it was in part because of the mathematics that his work inaugurated a revolution as theirs had not.

Copernicus' Physics and Cosmology

For Copernicus the motion of the earth was a by-product of the problem of the planets. He learned of the earth's motion by examining the celestial motions, and, because the celestial motions had to him a transcendent importance, he was little concerned about the difficulties that his innovation would present to normal men whose concerns were predominantly terrestrial. But Copernicus could not quite ignore the problems that the earth's motion raised for those whose sense of values was less exclusively astronomical than his own.

He had at least to make it possible for his contemporaries to conceive the earth's motion; he had to show that the consequences of this motion were not so devastating as they were commonly supposed to be. Therefore Copernicus opened the *De Revolutionibus* with a nontechnical sketch of the universe that he had constructed to house a moving earth. His introductory First Book was directed to laymen, and it included all the arguments that he thought he could make accessible to those without astronomical training.

Those arguments are profoundly unconvincing. Except when they derive from mathematical analyses that Copernicus failed to make explicit in the First Book, they were not new, and they did not quite conform to the details of the astronomical system that Copernicus was to develop in the later books. Only a man who, like Copernicus, had other reasons for supposing that the earth moved could have taken the First Book of the *De Revolutionibus* entirely seriously.

But the First Book is not unimportant. Its very weaknesses foreshadow the incredulity and ridicule with which Copernicus' system would be greeted by those who could not follow the detailed mathematical discussion of the subsequent books. Its repeated dependence upon Aristotelian and scholastic concepts and laws show how little even Copernicus was able to transcend his training and his times except in his own narrow field of specialization. Finally, the incompleteness and incongruities of the First Book illustrate again the coherence of traditional cosmology and traditional astronomy. Copernicus, who was led to revolution by astronomical motives only and who inevitably tried to restrict his innovation to astronomy, could not evade entirely the destructive cosmological consequences of the earth's motion.

BOOK ONE

1. *That the Universe is Spherical.*

In the first place we must observe that the Universe is spherical. This is either because that figure is the most perfect, as not being articulated but whole and complete in itself; or because it is the most capacious and therefore best suited for that which is to contain and preserve all things [of all solids with a given surface the sphere has the greatest volume]; or again because all the perfect parts of it, namely, Sun, Moon and Stars, are so formed; or because all things tend to assume this shape, as is seen in the case of drops of water and liquid bodies in general if freely formed. No one doubts that such a shape has been assigned to the heavenly bodies.

2. That the Earth also is Spherical.

The Earth also is spherical, since on all sides it inclines [or falls] toward the center. . . . As we pass from any point northward, the North Pole of the daily rotation gradually rises, while the other pole sinks correspondingly and more stars near the North Pole cease to set, while certain stars in the South do not rise. . . . Further, the change in altitude of the pole is always proportional to the distance traversed on the Earth, which could not be save on a spherical figure. Hence the Earth must be finite and spherical. . . . [Copernicus concludes the chapter with a few more arguments for the earth's sphericity typical of the classical sources that we have already examined.]

3. How Earth, with the Water on it, forms one Sphere.

The waters spread around the Earth form the seas and fill the lower declivities. The volume of the waters must be less than that of the Earth, else they would swallow up the land (since both, by their weight, press toward the same center). Thus, for the safety of living things, stretches of the Earth are left uncovered, and also numerous islands widely scattered. Nay, what is a continent, and indeed the whole of the Mainland, but a vast island? . . .

[Copernicus wishes, in this chapter, to show both that the terrestrial globe is predominantly made of earth and that water and earth together are required to make the globe a sphere. Presumably he is looking ahead. Earth breaks up less easily than water when moved; motion of a solid globe is more plausible than of a liquid one. Again, Copernicus will finally say that the earth moves naturally in circles because it is a sphere (see Chapter 8 of his First Book, below). He therefore needs to show that both earth and water are essential to the composition of the sphere, in order that both will participate together in the sphere's natural motion. The passage is of particular interest, because in documenting his view of the structure of the earth Copernicus displays his acquaintance with the recent voyages of discovery and with the corrections that must consequently be made in Ptolemy's geographical writings. For example, he says:

If the terrestrial globe were predominantly water,] the depth of Ocean would constantly increase from the shore outwards, and so neither island nor rock nor anything of the nature of land would be met by sailors, how far soever they ventured. Yet, we know that between the Egyptian Sea and the Arabian Gulf, well-nigh in the middle of the great land-mass, is a passage barely 15 stades wide. On the other hand, in his *Cosmography* Ptolemy would have it that the habitable land extends to the middle circle [of the earth, that is, through a hemisphere extending 180° eastward from the Canary Islands] with a *terra incognita* beyond where modern discovery has added Cathay and a very extensive region as far as 60° of longitude.

Thus we know now that the Earth is inhabited to a greater longitude than is left for Ocean.

This will more evidently appear if we add the islands found in our own time under the Princes of Spain and Portugal, particularly America, a land named after the Captain who discovered it and, on account of its unexplored size, reckoned as another Mainland – besides many other islands hitherto unknown. We thus wonder the less at the so-called Antipodes or Antichthones [the inhabitants of the other hemisphere]. For geometrical argument demands that the Mainland of America on account of its position be diametrically opposite to the Ganges basin in India. . . .

4. That the Motion of the Heavenly Bodies is Uniform, Circular, and Perpetual, or Composed of Circular Motions.

We now note that the motion of heavenly bodies is circular. Rotation is natural to a sphere and by that very act is its shape expressed. For here we deal with the simplest kind of body, wherein neither beginning nor end may be discerned nor, if it rotate ever in the same place, may the one be distinguished from the other.

Because there are a multitude of spheres, many motions occur. Most evident to sense is the diurnal rotation . . . marking day and night. By this motion the whole Universe, save Earth alone, is thought to glide from East to West. This is the common measure of all motions, since Time itself is numbered in days. Next we see other revolutions in contest, as it were, with this daily motion and opposing it from West to East. Such opposing motions are those of Sun and Moon and the five planets. . . .

But these bodies exhibit various differences in their motion. First their axes are not that of the diurnal rotation, but of the Zodiac, which is oblique thereto. Secondly, they do not move uniformly even in their own orbits; for are not Sun and Moon found now slower, now swifter in their courses? Further, at times the five planets become stationary at one point and another and even go backward. . . . Furthermore, sometimes they approach Earth, being then in *Perigee*, while at other times receding they are in *Apogee*.

Nevertheless, despite these irregularities, we must conclude that the motions of these bodies are ever circular or compounded of circles. For the irregularities themselves are subject to a definite law and recur at stated times, and this could not happen if the motions were not circular, for a circle alone can thus restore the place of a body as it was. So with the Sun which, by a compounding of circular motions, brings ever again the changing days and nights and the four seasons of the year. Now therein it must be that divers motions are conjoined, since a simple celestial body cannot move irregularly in a single circle. For such irregularity must come of unevenness either in the moving force (whether inherent or acquired) or in the form of the revolving body. Both these alike the mind abhors regarding the most perfectly disposed bodies.

It is then generally agreed that the motions of Sun, Moon, and Planets do but seem irregular either by reason of the divers directions of their axes of revolution, or else by reason that Earth is not the center of the circles in which they revolve, so that to us on Earth the displacements of these bodies [along their orbits] seem greater when they are near [the earth] than when they are more remote (as is demonstrated in optics [or in everyday observation – boats or carriages always seem to move by more quickly when they are closer]). Thus, equal [angular] motions of a sphere, viewed from different distances, will seem to cover different distances in equal times. It is therefore above all needful to observe carefully the relation of the Earth toward the Heavens, lest, searching out the things on high, we should pass by those nearer at hand, and mistakenly ascribe earthly qualities to heavenly bodies.

Copernicus here provides the fullest and most forceful version that we have yet examined of the traditional argument for restricting the motions of celestial bodies to circles. Only a uniform circular motion, or a combination of such motions, can, he thinks, account for the regular recurrence of all celestial phenomena at fixed intervals of time. So far every one of Copernicus' arguments is Aristotelian or scholastic, and his universe is indistinguishable from that of traditional cosmology. In some respects he is even more Aristotelian than many of his predecessors and contemporaries. He will not, for example, consent to the violation of the uniform and symmetric motion of a sphere that is implicit in the use of an equant.

The radical Copernicus has so far shown himself a thoroughgoing conservative. But he cannot postpone the introduction of the earth's motion any longer. He must now take account of his break with tradition. And strangely enough, it is in the break that Copernicus shows his dependence on the tradition most clearly. In dissent he still remains as nearly as possible an Aristotelian. Beginning in the fifth chapter, below, and culminating in the general discussion of motion in the eighth and ninth chapters, Copernicus suggests that because the earth is a sphere, like the celestial bodies, it too must participate in the compounded circular motions which, he says, are natural to a sphere.

5. *Whether Circular Motion belongs to the Earth; and concerning its position.*

Since it has been shown that Earth is spherical, we now consider whether her motion is conformable to her shape and her position in the Universe. Without these we cannot construct a proper theory of the heavenly phenomena. Now authorities agree that Earth holds firm her place at the center of the Universe, and they regard the contrary as unthinkable, nay as absurd. Yet if we examine more closely it will be seen that this question is not so settled, and needs wider consideration.

A seeming change of place may come of movement either of object or observer, or again of unequal movements of the two (for between equal and parallel motions no movement is perceptible). Now it is Earth from which the rotation of the Heavens is seen. If then some motion of Earth be assumed it will be reproduced in external bodies, which will seem to move in the opposite direction.

Consider first the diurnal rotation. By it the whole Universe, save Earth alone and its contents, appears to move very swiftly. Yet grant that Earth revolves from West to East, and you will find, if you ponder it, that my conclusion is right. It is the vault of Heaven that contains all things, and why should not motion be attributed rather to the contained than to the container, to the located than the locater? The latter view was certainly that of Heraclides and Ecphantus the Pythagorean and Hicetas of Syracuse (according to Cicero). All of them made the Earth rotate in the midst of the Universe, believing that the Stars set owing to the Earth coming in the way, and rise again when it has passed on.

If this [possibility of the earth's motion] is admitted, then a problem no less grave arises about the Earth's position, even though almost everyone has hitherto held that the Earth is at the center of the Universe. [Indeed, if the earth can move at all, it may have more than a simple axial motion about the center of the Universe. It may move away from the center altogether, and there are some good astronomical reasons for supposing that it does.] For grant that Earth is not at the exact center but at a distance from it which, while small compared [with the distance] to the starry sphere, is yet considerable compared with [the distances to] the spheres of the Sun and the other planets. Then calculate the consequent variations in their seeming motions, assuming these [motions] to be really uniform and about some center other than the Earth's. One may then perhaps adduce a reasonable cause for the irregularity of these variable motions. And indeed since the Planets are seen at varying distances from the Earth, the center of Earth is surely not the center of their circles. Nor is it certain whether the Planets move toward and away from Earth, or Earth toward and away from them. It is therefore justifiable to hold that the Earth has another motion in addition to the diurnal rotation. That the Earth, besides rotating, wanders with several motions and is indeed a Planet, is a view attributed to Philolaus the Pythagorean, no mean mathematician, and one whom Plato is said to have sought out in Italy.

Copernicus is here pointing to the most immediate advantage for astronomers of the concept of a moving earth. If the earth moves in an orbital circle around the center as well as spinning on its axis, then, at least qualitatively, the retrograde motions and the different times required for a planet's successive journeys around the ecliptic can be explained without the use of epicycles. In Copernicus' system the major irregularities of the planetary motions are only apparent. Viewed from a moving earth a planet that in fact moved regularly would appear to move irregularly. For this reason, Copernicus feels, we should believe in the orbital motion of the earth. But, strangely enough, in the parts of his work accessible to the lay reader, Copernicus never demonstrates this point any more clearly than he has above. Nor does he demonstrate the other astronomical advantages that he cites elsewhere. He asks the nonmathematical reader to take them for granted, though they are not difficult to demonstrate qualitatively. Only in the later books of the *De Revolutionibus* does he let the real advantages of his system show, and since he there deals, not with retrograde motions in general, but with the abstruse quantitative details of the retrograde motions of each individual planet, only the astronomically initiate were able to discover what the earlier references to astronomical advantages meant. Copernicus' obscurity may have been deliberate, for he had previously referred with some approval to the Pythagorean tradition which dictated withholding nature's secrets from those not previously purified by the study of mathematics (and by other more mystical rites). In any case, the obscurity helps explain the way in which his work was received.

In the next two sections we shall consider the astronomical consequences of the earth's motion in detail, but we must first complete Copernicus' general sketch of physics and cosmology. Omitting for the moment Chapter 6, *Of the Vastness of the Heavens compared with the Size of the Earth*, we proceed to the central chapters in which Copernicus, having asked indulgent readers to assume that astronomical arguments necessitate the earth's motion around the center, attempts to make that motion physically reasonable.

7. *Why the Ancients believed that the Earth is at rest, like a Center, in the Middle of the Universe.*

The ancient Philosophers tried by divers . . . methods to prove Earth fixed in the midst of the Universe. The most powerful argument was drawn from the doctrine of the heavy and the light. For, they argue, Earth is the heaviest element, and all things of weight move towards it, tending to its center. Hence since the Earth is spherical, and heavy things move vertically

to it, they would all rush together to the center if not stopped at the surface. Now those things which move towards the center must, on reaching it, remain at rest. Much more then will the whole Earth remain at rest at the center of the Universe. Receiving all falling bodies, it will remain immovable by its own weight.

Another argument is based on the supposed nature of motion. Aristotle says that motion of a single and simple body is simple. A simple motion may be either straight, or circular. Again a straight motion may be either up or down. So every simple motion must be either toward the center, namely downward, or away from the center, namely upward, or round the center, namely circular. [That is, according to Aristotelian and scholastic physics, natural motions, the only motions that can occur without an external push, are caused by the nature of the body that is in motion. The natural motion of each of the simple bodies (the five elements – earth, water, air, fire, and aether) must itself be simple, because it is a consequence of a simple or elementary nature. And, finally, there are only three (geometrically) simple motions within the spherical universe: up, down, circularly about the center.] Now it is a property only of the heavy elements earth and water to move downward, that is, to seek the center. But the light elements air and fire move upward away from the center. Therefore we must ascribe rectilinear motion to these four elements. The celestial bodies however have circular motion. So far Aristotle.

If then, says Ptolemy, Earth moves at least with a diurnal rotation, the result must be the reverse of that described above. For the motion must be of excessive rapidity, since in 24 hours it must impart a complete rotation to the Earth. Now things rotating very rapidly resist cohesion or, if united, are apt to disperse, unless firmly held together. Ptolemy therefore says that Earth would have been dissipated long ago, and (which is the height of absurdity) would have destroyed the Heavens themselves; and certainly all living creatures and other heavy bodies free to move could not have remained on its surface, but must have been shaken off. Neither could falling objects reach their appointed place vertically beneath, since in the meantime the Earth would have moved swiftly from under them. Moreover clouds and everything in the air would continually move westward. [Note that Copernicus has considerably elaborated Ptolemy's original argument, quoted on p. 85. It is by no means clear that Ptolemy would have gone this far.]

8. *The Insufficiency of these Arguments, and their Refutation.*

For these and like reasons, they say that Earth surely rests at the center of the Universe. Now if one should say that the Earth *moves*, that is as much as to say that the motion is natural, not violent [or due to an external push]; and things which happen according to nature produce the opposite effects to those which occur by violence. Things subjected to any force or impetus, gradual or sudden, must be disintegrated, and cannot long exist. But natural processes being adapted to their purpose work smoothly. [That is, if the earth moves at all, it does so because it is of the nature of earth to move, and a natural motion cannot be disruptive.]

Idle therefore is the fear of Ptolemy that Earth and all thereon would be disintegrated by a natural rotation, a thing far different from an artificial act. Should he not fear even more for the Universe, whose motion must be as much more rapid as the Heavens are greater than the Earth? Have the Heavens become so vast because of their vehement motion, and would they collapse if they stood still? If this were so the Heavens must be of infinite size. For the more they expand by the force of their motion, the more rapid will become the motion because of the ever increasing distance to be traversed in 24 hours. And in turn, as the motion waxes, must the immensity of the Heavens wax. Thus velocity and size would increase each the other to infinity. . . .

They say too that outside the Heavens is no body, no space, nay not even void, in fact absolutely nothing, and therefore no room for the Heavens to expand [as we have suggested above that they would]. Yet surely it is strange that something can be held by nothing. Perhaps indeed it will be easier to understand this nothingness outside the Heavens if we assume them to be infinite, and bounded internally only by their concavity, so that everything, however great, is contained in them, while the Heavens remain immovable. . . .

Let us then leave to Natural Philosophers the question whether the Universe be finite or no, holding only to this that Earth is finite and spherical. Why then hesitate to grant Earth that power of motion natural to its [spherical] shape, rather than suppose a gliding round of the whole universe, whose limits are unknown and unknowable? And why not grant that the diurnal rotation is only apparent in the Heavens but real in the Earth? It is but as the saying of Aeneas in Virgil – "We sail forth from the harbor, and lands and cities retire." As the ship floats along in the calm, all external things seem to have the motion that is really that of the ship, while those within the ship feel that they and all its contents are at rest.

It may be asked what of the clouds and other objects suspended in the air, or sinking and rising in it? Surely not only the Earth, with the water on it, moves thus, but also a quantity of air and all things so associated with the Earth. Perhaps the contiguous air contains an admixture of earthy or watery matter and so follows the same natural law as the Earth, or perhaps the air acquires motion from the perpetually rotating Earth by propinquity and absence of resistance. . . .

We must admit the possibility of a double motion of objects which fall and rise in the Universe, namely the resultant of rectilinear and circular motion. [This is the analysis advocated earlier by Oresme.] Thus heavy falling objects, being specially earthy, must doubtless retain the nature of the whole to which they belong. . . . [Therefore a stone, for example, when removed from the earth will continue to move circularly with the earth and will simultaneously fall rectilinearly toward the earth's surface. Its net motion will be some sort of spiral, like the motion of a bug that crawls straight toward the center of a rotating potter's wheel.]

That the motion of a simple body must be simple is true then primarily of circular motion, and only so long as the simple body rests in its own natural place and state. In that state no motion save circular is possible, for such motion is wholly self-contained and similar to being at rest. But if objects move or are moved from their natural place rectilinear motion supervenes. Now it is inconsistent with the whole order and form of the Universe that it should be outside its own place. Therefore there is no rectilinear motion save of objects out of their right place, nor is such motion natural to perfect objects, since [by such a motion] they would be separated from the whole to which they belong and thus would destroy its unity. . . . [Copernicus' argument shows how quickly the traditional distinction between the terrestrial and the celestial regions must disappear when the earth becomes a planet, for he is here simply applying a traditional argument about celestial bodies to the earth. Circular motion, whether simple or compound, is the nearest thing to rest. It can be natural to the earth just as it has always been natural to the heavens, because it cannot disrupt the observed unity and regularity of the universe. Linear motion, on the other hand, cannot be natural to any object that has achieved its own place, for linear motion is disruptive and a natural motion that destroys the universe is absurd.]

Further, we conceive immobility to be nobler and more divine than change and inconstancy, which latter is thus more appropriate to Earth than to the Universe. Would it not then seem absurd to ascribe motion to that which contains or locates, and not rather to that contained and located, namely the Earth?

Lastly, since the planets approach and recede from the Earth, both their motion round the center, which is held [by Aristotelians] to be the Earth, and also their motion outward and inward are the motion of one body. [And this violates the very laws from which Aristotelians derive the central position of the earth, for according to these laws the planets should have only a single motion.] Therefore we must accept this motion round the center in a more general sense, and must be satisfied provided that every motion has a proper center. From all these considerations it is more probable that the Earth moves than that it remains at rest. This is especially the case with the diurnal rotation, as being particularly a property of the Earth.

9. *Whether more than one Motion can be attributed to the Earth, and of the center of the Universe.*

Since then there is no reason why the Earth should not possess the power of motion, we must consider whether in fact it has more motions than one, so as to be reckoned as a Planet.

That Earth is not the center of all revolutions is proved by the apparently irregular motions of the planets and the variations in their distances from the Earth. These would be unintelligible if they moved in circles concentric with Earth. Since, therefore, there are more centers than one [that is, a center for all the orbital motions, a center of the earth itself, and perhaps others besides], we may discuss whether the center of the Universe is or is not the Earth's center of gravity.

Now it seems to me gravity is but a natural inclination, bestowed on the parts of bodies by the Creator so as to combine the parts in the form of a sphere and thus contribute to their unity and integrity. And we may believe this property present even in the Sun, Moon, and Planets, so that thereby they retain their spherical form notwithstanding their various paths. If, therefore, the Earth also has other motions, these must necessarily resemble the many outside [planetary] motions having a yearly period [since the earth now seems like a planet in so many other respects]. For if we transfer the motion of the Sun to the Earth, taking the Sun to be at rest, then morning and evening risings and settings of Stars will be unaffected, while the stationary points, retrogressions, and progressions of the Planets are due not to their own motions, but to that of the Earth, which their appearances reflect. Finally we shall place the Sun himself at the center of the Universe. All this is suggested by the systematic procession of events and the harmony of the whole Universe, if only we face the facts, as they say, "with both eyes open."

In these last three chapters we have Copernicus' theory of motion, a conceptual scheme that he designed to permit his transposing the earth and sun without tearing apart an essentially Aristotelian universe in the process. According to Copernicus' physics all matter, celestial and terrestrial, aggregates naturally into spheres, and the spheres then rotate of their own nature. A bit of matter separated from its natural position will continue to rotate with its sphere, simultaneously returning to its natural place by a rectilinear motion. It is a singularly incongruous theory (as Chapter 6 will demonstrate in more detail), and, in all but its most incongruous portions, it is a relatively unoriginal one. Copernicus may possibly have reinvented it for himself, but most of the essential elements in both his criticism of Aristotle and his theory of motion can be found in earlier scholastic writers, particularly in Oresme. Only when applied to Oresme's more limited problem, they are less implausible.

Failure to provide an adequate physical basis for the earth's motion does not discredit Copernicus. He did not conceive or accept the earth's motion for reasons drawn from physics. The physical and cosmological problem treated so crudely in the First Book are of his making, but they are not really his problems; he might have avoided them altogether if he could. But the inadequacies of Copernicus' physics do illustrate the way in which the consequences of his astronomical innovation transcend the astronomical problem from which the innovation was derived, and they do show how little the author of the innovation was himself able to assimilate the Revolution born from his work. The moving earth is an anomaly in a classical Aristotelian universe, but the universe of the *De Revolutionibus* is classical in every respect that Copernicus can make seem compatible with the motion of the earth. As he says himself, the motion of the sun has simply been transferred to the earth. The sun is not yet a star but the unique central body about which the universe is constructed; it inherits the old functions of the earth and some new ones besides. As we shall soon discover, Copernicus' universe is still finite, and concentric nesting spheres still move all planets, even though they can no longer be driven by the outer sphere, which is now at rest. All motions must be compounded of circles; moving the earth does not even enable Copernicus to dispense with epicycles. The Copernican Revolution, as we know it, is scarcely to be found in the *De Revolutionibus* and that is the second essential incongruity of the text.

Copernican Astronomy — The Two Spheres

We have not quite finished with Copernicus' First Book. But Chapters 10 and 11, which immediately follow the last section quoted above, deal with more nearly astronomical matters, and we shall consider them in the context of an astronomical discussion which goes beyond the arguments that Copernicus made accessible for lay readers. We shall again turn briefly to Copernicus' text in a later section, but first we shall try to discover why astronomers might have been more impressed than laymen with Copernicus' proposal. That can scarcely be discovered anywhere in the First Book.

Copernicus endowed the earth with three simultaneous circular motions: a diurnal axial rotation, an annual orbital motion, and an annual conical motion of the axis. The eastward diurnal rotation is the one that accounts for the apparent diurnal circles traced by the stars, sun, moon, and planets. If the earth is situated at the center of the sphere of the stars, and rotates eastward daily about an axis through its own north and south poles, then all objects that are stationary or nearly stationary with respect to the sphere of the stars will seem to travel westward in circular arcs above the horizon, arcs just like those in which the celestial bodies are observed to move in any short period of time.

If Copernicus' or Oresme's arguments to this effect are obscure, refer again to the star trails shown in Figures 6 and 7 (pp. 18 and 19). Those tracks could be produced either by a circular motion of the stars in front of a fixed observer (Ptolemy's explanation) or by a rotation of the observer in front of fixed stars (Copernicus' explanation). Or examine the new two-sphere universe shown in Figure 26, a

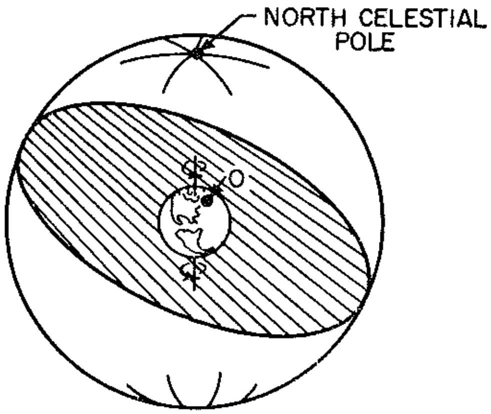

Figure 26. A rotating earth at the center of a fixed stellar sphere. In comparing this diagram with Figure 11, notice that here the horizon plane must be turned with the earth, so that its geometric relation to the moving observer *O* stays fixed.

simplified copy of the drawing that we first used in discussing the motions of stars in the two-sphere universe (Figure 11, p. 31) except that in the new version the poles are shown for the earth, not for the celestial sphere, and the direction of rotation has been reversed. When we first used a diagram like this, we held the earth, the observer, and the horizon plane fixed, and we turned the sphere of the stars westward. Now we must hold the outer sphere fixed and spin the earth, observer, and horizon plane together eastward. An observer sitting at the center of the horizon plane and moving with it will not be able to tell, at least from anything he can see in the skies, any difference between the two cases. In both he will see stars and planets

emerge along the eastern rim of the horizon and travel overhead to the western horizon in the same circular paths.

To this point we have kept the spinning earth at the center of the stationary sphere of the stars; we have, that is, considered the model of the universe suggested by Heraclides and developed by Oresme. This is only the first step toward a Copernican universe, however, and the next one is both more radical and more difficult. As Copernicus points out in the portion of Chapter 5 already quoted, if we are prepared to admit the possibility of the earth's motion at all, we must be prepared to consider not only a motion at the center, but also a motion of the earth away from the center. In fact, says Copernicus, a moving earth need not be at the center. It need only be relatively near the center, and as long as it stays close enough to the center it may move about at will without affecting the apparent motions of the stars. This was a difficult conclusion for his astronomically trained colleagues to accept because, in contrast to the conception of the earth's immobility, which derives only from common sense and from terrestrial physics, the notion of the earth's central position can apparently be derived directly from astronomical observation. Copernicus' conception of a noncentral earth therefore seemed initially to conflict with the immediate consequences of pure astronomical observation, and it was to avoid this conflict, or a closely related one which we shall consider at the end of the next section, that Copernicus was forced to increase vastly the size of the sphere of the stars and to take a first step toward the conception of an infinite universe elaborated by his successors. Copernicus' discussion of the earth's position occurs in Chapter 6 of his First Book. Here we shall need a clearer and more comprehensive version.

The earth's central position within the sphere of the stars can apparently be derived from the observation that the horizon of any terrestrial observer bisects the stellar sphere. The vernal equinox and the autumnal equinox are, for example, two diametrically opposite points on the sphere of the stars, for they are defined as the intersections of two great circles on the sphere, the equator and the ecliptic. Observation shows that whenever one of these points is just rising over the horizon on the east, the other is just setting in the west. The same is true of any other pair of diametrically opposite points on the sphere: whenever one rises, the other sets. Apparently these observations can be explained only if, as shown in Figure 26 or the earlier Figure 11, the horizon plane is drawn through the center of the sphere of the stars so that it, too, will intersect the sphere in a great circle. If and only if the horizon plane intersects the sphere of the stars in a great circle will diametrically opposite points on the sphere always rise and set at the same moment.

But all horizon planes must also be drawn tangent to the spherical earth. (We have avoided this construction in Figures 26 and 11 only because we have there shown the earth immensely exaggerated in size.) Therefore the observer must himself be at, or very nearly at, the center of the sphere of the stars. The entire surface of the terrestrial sphere itself must be at or very nearly at the center; the earth must be very small, almost a point, and it must be centrally located. If, as in Figure 27, the earth (represented by the inner concentric

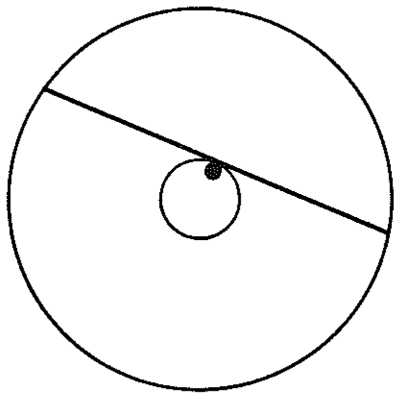

Figure 27. If the earth's diameter is appreciable compared with that of the sphere of the stars or if the earth is appreciably displaced from the center, the horizon plane does not bisect the stellar sphere.

circle) were quite large with respect to the sphere of the stars or if the earth (now represented by the black dot) were small but displaced from the center, then the horizon plane would not seem to bisect the sphere of the stars, and diametrically opposite points on the sphere would not rise and set together.

As developed here the argument itself makes clear the weakness exploited by Copernicus. Observation does not show that the earth must be a point (if it did, even the Aristotelian and Ptolemaic universe would conflict with observation) or that it must be precisely at the center, because observation can never say that, for example, the vernal equinox rises *exactly* as the autumnal equinox sets. Crude naked-eye observations will show that when the vernal equinox is just setting, the autumnal equinox is within a degree or so of the horizon. Refined naked-eye observation (appropriately corrected for atmospheric refraction and for the irregularities of any actual horizon) might show that when the winter solstice has just reached the western horizon, the summer solstice is within 6′ (or 0.1°) of the eastern horizon. But no naked-eye observation will do much better. It can show only that the horizon *very nearly* bisects the sphere and that all terrestrial observers must therefore be very close to the center of the universe. Just how nearly the horizon bisects the sphere and just how close to the center terrestrial observers must be depends upon the accuracy of observation.

For example, if we know from observation that whenever one solstice lies on the horizon, the other is *no more than* 0.1° away from the horizon, then no terrestrial observer may ever be farther from the center of the sphere of the stars than a distance which is 0.001 the radius of that sphere. Or if observation tells us (and few naked-eye observations are even approximately this good) that with one solstice on the horizon the other is no more than 0.01° away from the horizon, then the inner sphere of Figure 27 may have a radius no larger than 0.0001 the radius of the outer sphere, and the entire earth must again lie somewhere within the inner circle at all times. If the earth moved outside the inner circle, then the horizon plane would fail to bisect the sphere of the stars by more than 0.01°, and our hypothetical observations would discover the discrepancy, but with the earth anywhere inside of the inner circle, the horizon plane will seem, within the limits of observation, to bisect the sphere.

That is Copernicus' argument. Observation only forces us to keep the earth somewhere inside of a small sphere concentric with the sphere of the stars. Within that inner sphere the earth may move freely without violating the appearances. In particular, the earth may have an orbital motion about the center or about the central sun, provided that its orbit never carries it too far away from the center. And "too far" means only "too far relative to the radius of the outer sphere." If the radius of the outer sphere is known, then observations of known accuracy place a limit upon the *maximum* radius of the earth's orbit. If the size of the earth's orbit is known (and it can, in theory, be determined by Aristarchus' technique for measuring the earth-sun distance), then observations of known accuracy place a limit upon the *minimum* size of the sphere of the stars. For example, if the distance between the earth and sun is, as indicated by Aristarchus' measurement described in the Technical Appendix, equal to 764 earth diameters (1528 earth radii) and if observations are known to be accurate within 0.1°, then the radius of the sphere of the stars must be at least 1000 times the radius of the earth's orbit or at least 1,528,000 earth radii.

Our example is a useful one, because, though Copernicus' observations were not quite this accurate, those made by his immediate successor, Brahe, were if anything slightly more accurate than 0.1°. Ours is a representative estimate of the minimum size of the sphere of the stars by a sixteenth-century Copernican. In principle, there is nothing absurd about the result, for in the sixteenth and seventeenth centuries there was no direct way of determining the distance to the sphere of the stars. Its radius might have been more than 1,500,000 earth radii. But if it were that large – and Copernicanism demanded that it should be – then a real break with traditional cosmology must be admitted. Al Fargani, for example, had estimated the radius of the sphere as 20,110 earth radii, more than seventy-five times smaller than the Copernican estimate. The Copernican universe must be vastly larger than that of traditional cosmology. Its volume is *at least* 400,000 times as great. There is an immense amount of space between the sphere of Saturn and the sphere of the stars. The neat functional coherence of the nesting spheres of the traditional universe has been violated, though Copernicus seems to remain sublimely unaware of the break.

Copernican Astronomy — The Sun

Copernicus' argument permits an orbital motion of the earth in a vastly expanded universe, but the point is academic unless the orbital motion can be shown to be compatible with the observed motions of the sun and other planets. It is to those motions that Copernicus turns in Chapters 10 and 11 of his First Book. We may best begin with an expanded paraphrase of Chapter 11, in which

Copernicus describes the orbital motion of the earth and considers its effect upon the apparent position of the sun. For the moment assume, as shown in Figure 28, that the centers of the universe, the sun, and the earth's orbit all coincide. In the diagram the plane of the ecliptic is viewed from a position near the north celestial pole; the sphere of the stars is stationary; the earth travels regularly eastward in its orbit once in a year; and it simultaneously spins eastward on its axis once in every 23 hours 56 minutes. Provided that the earth's orbit is much

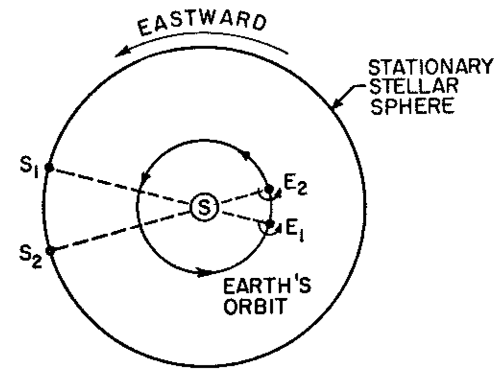

Figure 28. As the earth moves in its Copernican orbit from E_1 to E_2, the apparent position of the central sun, *S*, seen against the sphere of the stars shifts from S_1 to S_2.

smaller than the sphere of the stars, the axial rotation of the earth will account precisely for the diurnal circles of the sun, moon, and planets, as well as for those of the stars, because from any position in the earth's orbit all of these bodies must be seen against the sphere of the stars and must seem to move with it as the earth rotates.

In the diagram the earth is shown in two positions which it occupies thirty days apart. In each position the sun is viewed against the sphere of the stars, and both apparent positions of the sun must lie on the ecliptic, which is now defined as the line in which the plane of the earth's motion (a plane that includes the sun) intersects the sphere. But as the earth has moved eastward from position E_1 to position E_2 in the diagram, the sun has apparently moved eastward along the ecliptic from position S_1 to position S_2. Copernicus' theory therefore predicts just the same eastward annual motion of the sun along the ecliptic as the Ptolemaic theory. It also predicts, as we shall discover immediately, the same seasonal variation of the height of the sun in the sky.

Figure 29 shows the earth's orbit viewed from a point in the celestial sphere slightly north of the autumnal equinox. The earth is drawn at the four positions occupied successively at the vernal equinox, the summer solstice, the autumnal equinox, and the winter solstice. In all four of these positions, as throughout its motion, the earth's axis remains parallel to an imaginary line passing through the sun and tilted 23½° from a perpendicular to the plane of the ecliptic. Two

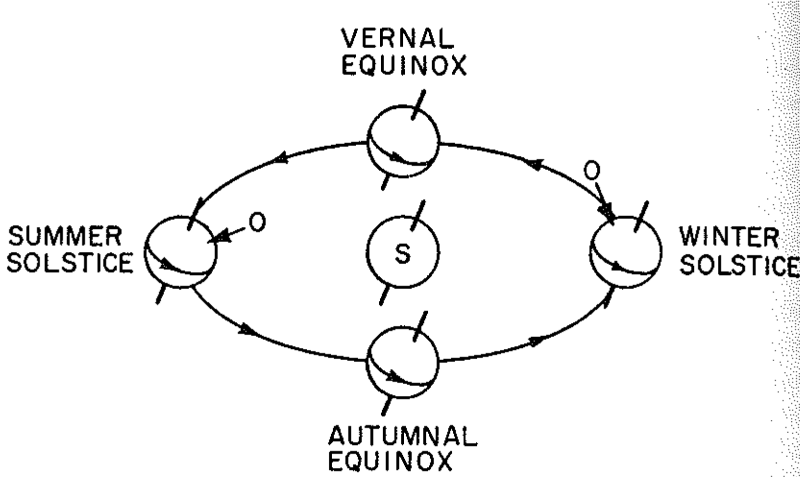

Figure 29. The earth's annual motion around its Copernican orbit. At all times the earth's axis stays parallel to itself or to the stationary line drawn through the sun. As a result an observer *O* at noon in middle-northern latitudes finds the sun much more nearly overhead at the summer than at the winter solstice.

little arrows in the diagram show the position of a terrestrial observer in middle-northern latitudes at local noon on June 22 and December 22, the two solstices. Lines from the sun to the earth (not shown in the diagram) indicate the direction of the rays of the noon sun, which is clearly more nearly over the observer's head during the summer solstice than during the winter solstice. A similar construction determines the sun's elevation at the equinoxes and at intermediate seasons.

The seasonal variation of the sun's elevation can therefore be completely diagnosed from Figure 29. In practice, however, it is simpler to revert to the Ptolemaic explanation. Since in every season

the sun appears to occupy the same position among the stars in the Copernican as in the Ptolemaic system, it must rise and set with the same stars in both systems. The correlation of the seasons with the apparent position of the sun along the ecliptic cannot be affected by the transition. With respect to the apparent motions of the sun and stars the two systems are equivalent, and the Ptolemaic is simpler.

The last diagram also reveals two other interesting features of Copernicus' system. Since it is the rotation of the earth that produces the diurnal circles of the stars, the earth's axis must point to the center of those circles in the celestial sphere. But, as the diagram indicates, the earth's axis never does point to quite the same positions on the celestial sphere from one year's end to the next. According to the Copernican theory the extension of the earth's axis traces, during the course of a year, two small circles on the sphere of the stars, one around the north celestial pole and one around the south. To an observer on the earth the center of the diurnal circles of the stars should itself seem to move in a small circle about the celestial pole once each year. Or, to put the same point in a way more closely related to observation, each of the stars should seem slightly to change its position on the sphere of the stars (or with respect to the observed pole of the sphere) during the course of a year.

This apparent motion, which cannot be seen with the naked eye and which was not even seen with telescopes until 1838, is known as

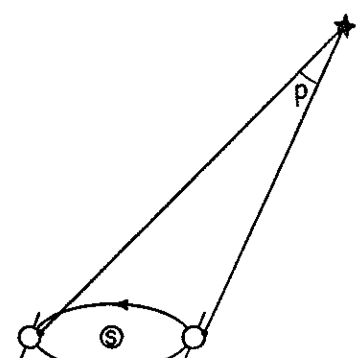

Figure 30. The annual parallax of a star. Because the line between a terrestrial observer and a fixed star does not stay quite parallel to itself as the earth moves in its orbit, the star's apparent position on the stellar sphere should shift by an angle *p* during an interval of six months.

the parallactic motion. Because two lines drawn to a star from diametrically opposite points on the earth's orbit are not quite parallel (Figure 30), the apparent angular position of the star viewed from the earth should be different at different seasons. But if the distance to the star is very much greater than the distance across the earth's orbit, then the angle of parallax, p in Figure 30, will be very, very small, and the change in the apparent position of the star will not be appreciable. The parallactic motion is not apparent only because the stars are so very far away relative to the dimensions of the earth's orbit. The situation is precisely equivalent to the one we discussed above when considering why the earth's motion did not seem to change the intersection of the horizon plane and the sphere of the stars. In fact, we are dealing with the same problem. But the present version of the problem is a more important one, because near the horizon it is very difficult to make the precise measurements of stellar position required to discover whether the horizon bisects the stellar sphere. Unlike the rising and setting of the equinoxes, discussed above, the search for parallactic motions need not be restricted to the horizon. Parallax therefore provides a much more sensitive observational check upon the minimum size of the sphere of the stars relative to the size of the earth's orbit than is provided by the position of the horizon, and the Copernican estimates of the sphere's size given above ought really to have been derived from a discussion of parallax.

The second point illuminated by considering Figure 29 is not about the skies at all but about Copernicus. We described the orbital motion illustrated in the diagram as a single motion by which the earth's center is carried in a circle about the sun while its axis remains always parallel to a fixed line through the sun. Copernicus describes the same physical motion as consisting of two simultaneous mathematical motions. That is why he gives the earth a total of three circular motions. And the reasons for his description give another significant illustration of the extent to which his thought was bound to the traditional patterns of Aristotelian thought. For him the earth is a planet which is carried about the central sun by a sphere just like the one that used to carry the sun about the central earth. If the earth were firmly fixed in a sphere, its axis would not always stay parallel to the same line through the sun; it would instead be carried about by the sphere's rotation and would occupy the positions shown

in Figure 31*a*. After the earth had revolved 180° about the sun, the earth's axis would still be tilted 23½° away from the perpendicular but in a direction opposite to that in which it had begun. To undo this change in the direction of the axis, caused by the rotation of the

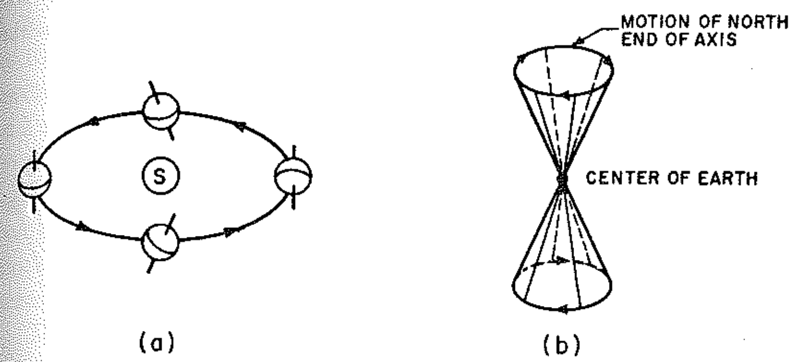

Figure 31. Copernicus' "second" and "third" motions. The second motion, that of a planet fixed in a rotating sun-centered sphere, is shown in (*a*). This motion does not keep the earth's axis parallel to itself, so that the conical third motion shown in (*b*) is required to bring the axis back into line.

sphere that carries the earth, Copernicus requires a third circular motion, this one applied to the axis of the earth only and shown in Figure 31*b*. It is a conical motion, which carries the north end of the axis once westward each year, and thus just compensates for the effect on the earth's axis of the orbital motion.

Copernican Astronomy — The Planets

So far the conceptual scheme developed by Copernicus is just as effective as Ptolemy's, but it is surely no more so, and it seems a good deal more cumbersome. It is only when the planets are added to Copernicus' universe that any real basis for his innovation becomes apparent. Consider, for example, the explanation of retrograde motion to which Copernicus alluded without discussion at the end of Chapter 5 in his introductory First Book. In the Ptolemaic system the retrograde motion of each planet is accounted for by placing the planet on a major epicycle whose center is, in turn, carried about the earth by the planet's deferent. The combined motion of these two circles produces the characteristic looped patterns discussed in Chapter 3.

In Copernicus' system no major epicycles are required. The retrograde or westward motion of a planet among the stars is only an apparent motion, produced, like the apparent motion of the sun around the ecliptic, by the orbital motion of the earth. According to Copernicus the motion that Ptolemy had explained with major epicycles was really the motion of the earth, attributed to the planets by a terrestrial observer who thought himself stationary.

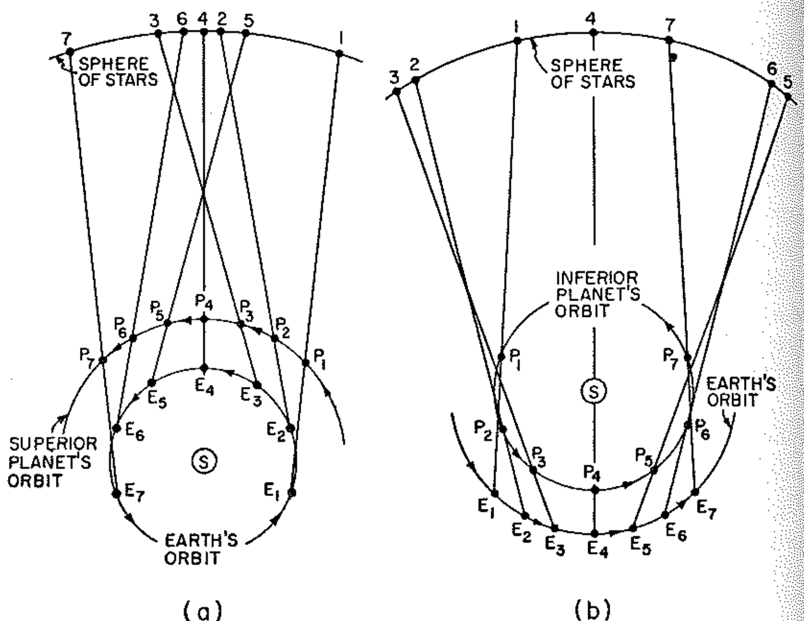

Figure 32. The Copernican explanation of retrograde motion for (*a*) superior planets and (*b*) inferior planets. In each diagram the earth moves steadily on its orbit from E_1 to E_7 and the planet moves from P_1 to P_7. Simultaneously the planet's apparent position against the stellar sphere shifts eastward from 1 to 7, but as the two planets pass there is a brief westward retrogression from 3 to 5.

The basis of Copernicus' contention is illustrated and clarified by Figures 32*a* and 32*b*. Successive apparent positions of a moving superior planet viewed from a moving earth against the fixed background provided by the stellar sphere are shown in the first diagram; the second shows successive apparent positions of an inferior planet. Only the orbital motions are indicated; the earth's diurnal rotation, which produces the rapid apparent westward motion of the sun, planets, and stars together, is omitted. In both diagrams successive positions

of the earth in its sun-centered circular orbit are indicated by the points $E_1, E_2, \ldots, E_7$; the corresponding consecutive positions of the planets are marked $P_1, P_2, \ldots, P_7$; and the corresponding apparent positions of the planet, discovered by extending a line from the earth through the planet until it intersects the stellar sphere, are labeled 1, 2, . . . , 7. In each case the more central planet moves more rapidly in its orbit. Inspection of the diagram indicates that the apparent motion of the planet among the stars is normal (eastward) from 1 to 2 and from 2 to 3; then the planet appears to retrogress (move westward) from 3 to 4 and from 4 to 5; and finally it reverses its motion again and moves normally from 5 to 6 and from 6 to 7. As the earth completes the balance of its orbit, the planet continues in normal motion, moving eastward most rapidly when it lies diametrically across the sun from the earth.

Therefore, in Copernicus' system, planets viewed from the earth should appear to move eastward most of the time; they retrogress only when the earth, in its more rapid orbital motion, overtakes them (superior planets) or when they overtake the earth (inferior planets). Retrograde motion can occur only when the earth is nearest to the planet whose motion is observed, and this is in accord with observations. Superior planets, at least, are most brilliant when they move westward. The first major irregularity of planetary motion has been explained qualitatively without the use of epicycles.

Figure 33 indicates how Copernicus' proposal accounts for a second major irregularity of the planetary motions – the discrepancy between the times required for successive trips of a planet around the ecliptic. In the diagram it is assumed that the earth completes 1¼ eastward trips about its orbit while the planet, in this case a superior planet, travels eastward through its orbit once. Suppose that at the start of the series of observations the earth is at E_1 and the planet at P. The planet is then in the middle of a retrogression and appears silhouetted against the stationary stellar sphere at 1. When the planet has completed one revolution in its orbit and returned to P, the earth has made 1¼ trips around its orbit and reached E_2. The planet therefore is seen at 2, west of position 1 at which it started. It has not yet completed a full journey around the ecliptic, and its first full trip will therefore consume more time than the planet required to revolve once in its orbit.

As the planet makes its second trip about its orbit, the earth again makes more than one orbital revolution and reaches E_3 when the planet has returned to *P* again. This time the planet is seen silhouetted at 3, to the east of position 2. It has completed more than one journey around the ecliptic while moving only once through its orbit, and its second journey around the ecliptic was therefore a very rapid one. After a third revolution the planet is again at *P*, but it appears at position 4, east of 3, and its journey around the ecliptic was therefore

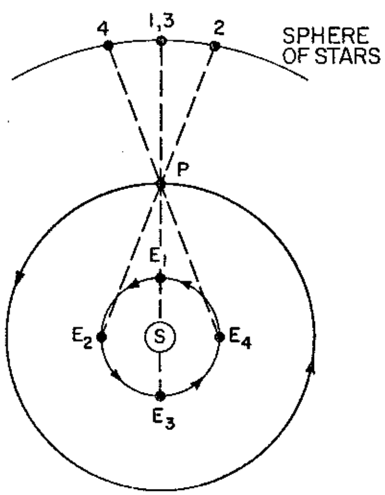

Figure 33. The Copernican explanation of variations in the time required for a superior planet to complete successive journeys around the ecliptic. While the planet moves once eastward around its orbit from *P* to *P*, the earth makes 1¼ eastward revolutions from E_1 to E_1 and on to E_2. During this interval the apparent position of the planet among the stars moves eastward from 1 to 2, slightly less than a full trip. During the planet's next revolution the earth moves from E_2 to E_2 and on to E_3, so that its apparent position among the stars shifts from 2 to 1 and on to 1 again, slightly more than one full trip around the ecliptic.

again a fast one. After a fourth revolution in its orbit the planet again appears at 1, west of 4, and its final trip was therefore slow. The planet has completed four trips about its orbit and four trips around the ecliptic at the same instant. The average time required by a superior planet to circle the ecliptic is therefore identical with the planet's orbital period. But the time required for an individual trip may be considerably greater or considerably less than the average. A similar argument will account for the similar irregularities of an inferior planet's motion.

Retrograde motion and the variation of the time required to circle

the ecliptic are the two gross planetary irregularities which in antiquity had led astronomers to employ epicycles and deferents in treating the problem of the planets. Copernicus' system explains these same gross irregularities, and it does so without resorting to epicycles, or at least to major epicycles. To gain even an approximate and qualitative account of the planetary motions Hipparchus and Ptolemy had required twelve circles – one each for the sun and moon, and two each for the five remaining "wanderers." Copernicus achieved the same qualitative account of the apparent planetary motions with only seven circles. He needed only one sun-centered circle for each of the six known planets – Mercury, Venus, Earth, Mars, Jupiter, and Saturn – and one additional earth-centered circle for the moon. To an astronomer concerned only with a qualitative account of the planetary motions, Copernicus' system must seem the more economical.

But this apparent economy of the Copernican system, though it is a propaganda victory that the proponents of the new astronomy rarely failed to emphasize, is largely an illusion. We have not yet begun to deal with the full complexity of Copernicus' planetary astronomy. The seven-circle system presented in the First Book of the *De Revolutionibus*, and in many modern elementary accounts of the Copernican system, is a wonderfully economical system, but it does not work. It will not predict the position of planets with an accuracy comparable to that supplied by Ptolemy's system. Its accuracy is comparable to that of a simplified twelve-circle version of Ptolemy's system – Copernicus can give a more economical *qualitative* account of the planetary motions than Ptolemy. But to gain a reasonably good *quantitative* account of the alteration of planetary position Ptolemy had been compelled to complicate the fundamental twelve-circle system with minor epicycles, eccentrics, and equants, and to get comparable results from his basic seven-circle system Copernicus, too, was forced to use minor epicycles and eccentrics. His full system was little if any less cumbersome than Ptolemy's had been. Both employed over thirty circles; there was little to choose between them in economy. Nor could the two systems be distinguished by their accuracy. When Copernicus had finished adding circles, his cumbersome sun-centered system gave results as accurate as Ptolemy's, but it did not give more accurate results. Copernicus did not solve the problem of the planets.

The full Copernican system is described in the latter books of the *De Revolutionibus*. Fortunately we need only illustrate the sorts of complexities there developed. Copernicus' system was not, for example, really a sun-centered system at all. To account for the increased rate at which the sun travels through the signs of the zodiac during the winter, Copernicus made the earth's circular orbit eccentric, displacing its center from the sun's. To account for other irregularities, indicated by ancient and contemporary observations of the sun's motion, he kept this displaced center in motion. The center of the earth's eccentric was placed upon a second circle whose motion continually varied the extent and direction of the earth's eccentricity. The final system employed to compute the earth's motion is represented approximately in Figure 34*a*. In the diagram, S is the sun, fixed in space; the point *O*, which itself moves slowly about the sun, is the center of a slowly rotating circle that carries the moving center O_E of the earth's eccentric; *E* is the earth itself.

Similar complexities were necessitated by the observed motions of the other heavenly bodies. For the moon Copernicus used a total of three circles, the first centered on the moving earth, the second centered on the moving circumference of the first, and the third on the

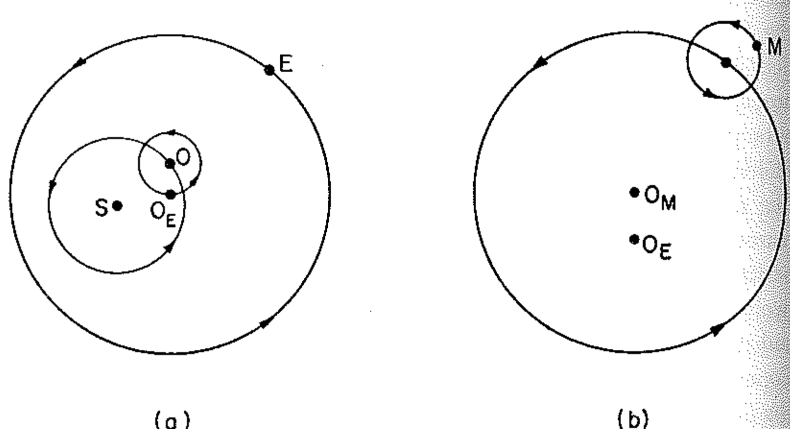

Figure 34. Copernicus' account of the motion of (*a*) the earth and (*b*) Mars. In (*a*) the sun is at S, and the earth, *E*, revolves on a circle whose center, O_E, revolves slowly about a point *O*, which in turn revolves on a sun-centered circle. In (*b*) Mars is placed on an epicycle revolving on a deferent whose center, O_M, maintains a fixed geometric relation to the moving center O_E of the earth's orbit.

circumference of the second. For Mars and most of the other planets he employed a system much like that illustrated in Figure 34*b*. The center of Mars's orbit, O_M, is displaced from the center of the earth's orbit, O_E, and is moved with it; the planet itself is placed at *M*, not on the eccentric but on an epicycle, which rotates eastward in the same direction and with the same period as the eccentric. Nor do the complexities end here. Still other devices, fully equivalent to Ptolemy's, were required to account for the north and south deviations of each planet from the ecliptic.

Even this brief sketch of the complex system of interlocking circles employed by Copernicus to compute planetary position indicates the third great incongruity of the *De Revolutionibus* and the immense irony of Copernicus' lifework. The preface to the *De Revolutionibus* opens with a forceful indictment of Ptolemaic astronomy for its inaccuracy, complexity, and inconsistency, yet before Copernicus' text closes, it has convicted itself of exactly the same shortcomings. Copernicus' system is neither simpler nor more accurate than Ptolemy's. And the methods that Copernicus employed in constructing it seem just as little likely as the methods of Ptolemy to produce a single consistent solution of the problem of the planets. The *De Revolutionibus* itself is not consistent with the single surviving early version of the system, described by Copernicus in the early manuscript *Commentariolus*. Even Copernicus could not derive from his hypothesis a single and unique combination of interlocking circles, and his successors did not do so. Those features of the ancient tradition which had led Copernicus to attempt a radical innovation were not eliminated by that innovation. Copernicus had rejected the Ptolemaic tradition because of his discovery that "the Mathematicians are inconsistent in these [astronomical] investigations" and because "if their hypotheses were not misleading, all inferences based thereon might surely be verified." A new Copernicus could have turned the identical arguments against him.

The Harmony of the Copernican System

Judged on purely practical grounds, Copernicus' new planetary system was a failure; it was neither more accurate nor significantly simpler than its Ptolemaic predecessors. But historically the new system was a great success; the *De Revolutionibus* did convince a few of Copernicus' successors that sun-centered astronomy held the key to the problem of the planets, and these men finally provided the simple and accurate solution that Copernicus had sought. We shall examine their work in the next chapter, but first we must try to discover why they became Copernicans – in the absence of increased economy or precision, what reasons were there for transposing the earth and the sun? The answer to this question is not easily disentangled from the technical details that fill the *De Revolutionibus*, because, as Copernicus himself recognized, the real appeal of sun-centered astronomy was aesthetic rather than pragmatic. To astronomers the initial choice between Copernicus' system and Ptolemy's could only be a matter of taste, and matters of taste are the most difficult of all to define or debate. Yet, as the Copernican Revolution itself indicates, matters of taste are not negligible. The ear equipped to discern geometric harmony could detect a new neatness and coherence in the sun-centered astronomy of Copernicus, and if that neatness and coherence had not been recognized, there might have been no Revolution.

We have already examined one of the aesthetic advantages of Copernicus' system. It explains the principal *qualitative* features of the planetary motions without using epicycles. Retrograde motion, in particular, is transformed to a natural and immediate consequence of the geometry of sun-centered orbits. But only astronomers who valued qualitative neatness far more than quantitative accuracy (and there were a few – Galileo among them) could consider this a convincing argument in the face of the complex system of epicycles and eccentrics elaborated in the *De Revolutionibus*. Fortunately there were other, less ephemeral, arguments for the new system. For example, it gives a simpler and far more natural account than Ptolemy's of the motions of the inferior planets. Mercury and Venus never get very far from the sun, and Ptolemaic astronomy accounts for this observation by tying the deferents of Mercury, Venus, and the sun together so that the center of the epicycle of each inferior planet always lies on a straight line between the earth and the sun (Figure 35*a*). This alignment of the centers of the epicycles is an "extra" device, an *ad hoc* addition to the geometry of earth-centered astronomy, and there is no need for such an assumption in Copernicus' system. When, as in

Figure 35*b*, the orbit of a planet lies entirely within the earth's orbit, there is no way in which the planet can appear far from the sun. Maximum elongation will occur when, as in the diagram, the line from the earth to the planet is tangent to the planet's orbit and the angle *SPE* is a right angle. Therefore the angle of elongation, *SEP*, is the largest angle by which the inferior planet can deviate from the sun. The basic geometry of the system fully accounts for the way in which Mercury and Venus are bound to the sun.

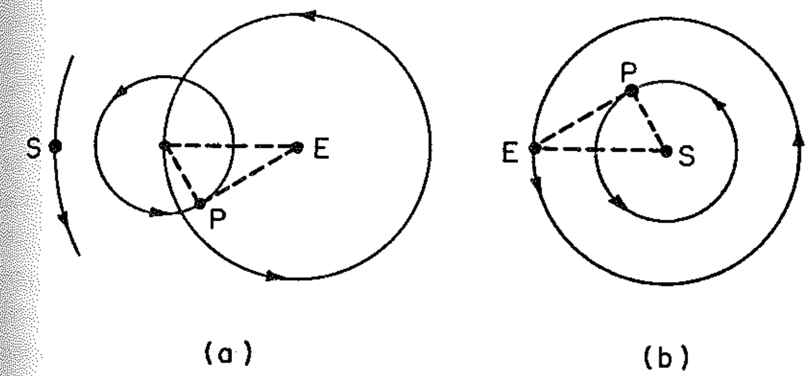

Figure 35. Limited elongation of inferior planets explained in (*a*) the Ptolemaic and (*b*) the Copernican systems. In the Ptolemaic system the angle between the sun, S, and the planet, *P*, must be restricted by keeping the center of the epicycle on the line between the earth and the sun. In the Copernican system, with the planet's orbit entirely contained by the earth's, no such restriction is necessary.

Copernican geometry illuminates another even more important aspect of the behavior of the inferior planets, namely, the order of their orbits. In the Ptolemaic system the planets were arranged in earth-centered orbits so that the average distance between a planet and the earth increased with the time required for the planet to traverse the ecliptic. The device worked well for the superior planets and for the moon, but Mercury, Venus, and the sun all require 1 year for an average journey around the ecliptic, and the order of their orbits had therefore always been a source of debate. In the Copernican system there is no place for similar debate; no two planets have the same orbital period. The moon is no longer involved in the problem, for it travels about the earth rather than about the central sun. The superior planets, Mars, Jupiter, and Saturn, preserve their old order about the new center, because their orbital periods are the same as the average lengths of time they need to circle the ecliptic. The earth's orbit lies inside of Mars's, since the earth's orbital period, 1 year, is less than Mars's 687 days. It only remains to place Mercury and Venus in the system, and their order is, for the first time, uniquely determined.

This can be seen as follows. Venus is known to retrogress every 584 days, and since retrograde motion can be observed only when Venus passes the earth, 584 days must be the time Venus requires to lap the earth once in their common circuit of the sun. Now in 584 days the earth has traversed its orbit $\frac{584}{365}$ $(=1\frac{219}{365})$ times. Since Venus has lapped the earth once during this interval, it must have circled its orbit $2\frac{219}{365}(=\frac{949}{365})$ times in just 584 days. But a planet that circles its orbit $\frac{949}{365}$ times in 584 days must require $584\times\frac{365}{949}(=225)$ days to circle its orbit once. Therefore, since Venus's period, 225 days, is less than earth's, Venus's orbit must be inside the earth's, and there is no ambiguity. A similar calculation places Mercury's orbit inside Venus's and closest to the sun. Since Mercury retrogresses, and therefore laps the earth, every 116 days, it must complete its orbit just $1\frac{116}{365}(=\frac{481}{365})$ times in 116 days. Therefore it will complete its orbit just once in $116\times\frac{365}{481}$ $(=88)$ days. Its orbital period of 88 days is the shortest of all, and it is therefore the planet closest to the sun.

So far we have ordered the sun-centered planetary orbits with the same device used by Ptolemaic astronomers to order earth-centered orbits: planets farther from the center of the universe take longer to circle the center. The assumption that the size of the orbit increases with orbital period can be applied more fully in the Copernican than in the Ptolemaic system, but in both systems it is initially arbitrary. It seems natural that planets should behave this way, like Vitruvius' ants on a wheel, but there is no necessity that they do so. Perhaps the assumption is entirely gratuitous, and the planets, excepting the sun and moon, whose distances can be directly determined, have another order.

The response to this suggested reordering constitutes another very important difference between the Copernican and the Ptolemaic systems, and one which, as we discovered in his preface, Copernicus

himself particularly emphasizes. In the Ptolemaic system the deferent and epicycle of any one planet can be shrunk or expanded at will without affecting either the sizes of the other planetary orbits or the position at which the planet, viewed from a central earth, appears against the stars. The order of the orbits *may be* determined by assuming a relation between size of orbit and orbital period. In addition, the relative dimensions of the orbits *may be* worked out with the aid of the further assumption, discussed in Chapter 3, that the minimum distance of one planet from the earth is just equal to the maximum distance between the earth and the next interior planet. But though both of these seem natural assumptions, neither is necessary. The Ptolemaic system could predict the same apparent positions for the planets without making use of either. In the Ptolemaic system the appearances are not dependent upon the order or the sizes of the planetary orbits.

There is no similar freedom in the Copernican system. If all the planets revolve in approximately circular orbits about the sun, then both the order and the relative sizes of the orbits can be determined directly from observation without additional assumptions. Any change in order or even in relative size of the orbits will upset the whole system. For example, Figure 36*a* shows an inferior planet, *P*, viewed from the earth at the time when it reaches its maximum elongation from the sun. The orbit is assumed circular, and the angle *SPE* must therefore be a right angle when the angle of elongation, *SEP*, reaches its maximum value. The planet, the sun, and the earth form a right triangle one of whose acute angles, *SEP*, can be directly measured. But knowledge of one acute angle of a right triangle determines the ratio of the lengths of the sides of that triangle. Therefore the ratio of the radius of the inferior planet's orbit, *SP*, to the radius of the earth's orbit, *SE*, can be computed from the measured value of the angle *SEP*. The relative sizes of the earth's orbit and the orbits of both inferior planets can be discovered from observation.

An equivalent determination can be made for a superior planet, though the techniques are more complex. One possible technique is illustrated in Figure 36*b*. Suppose that at some determined instant of time the sun, the earth, and the planet all lie on the straight line *SEP*; this is the orientation in which the planet lies diametrically across the ecliptic from the sun and is in the middle of a retrograde motion. Since the earth traverses its orbit more rapidly than any su-

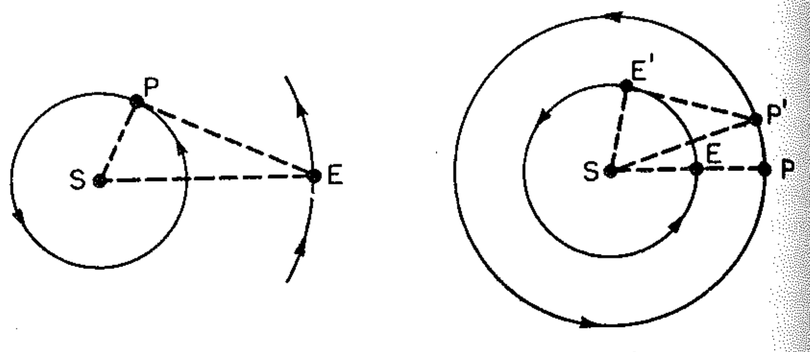

Figure 36. Determining the relative dimensions of orbits in the Copernican system: (*a*) for an inferior planet; (*b*) for a superior planet.

perior planet, there must be some later instant of time when the earth at *E′* and the planet at *P′* will form a right angle *SE′P′* with the sun, and since *SE′P′* is the angle between the sun and the superior planet viewed from the earth, it can be directly determined and the time required to achieve it can be measured. The angle *ESE′* can now be determined, for it must bear the same ratio to 360° as the time required by the earth to move from *E* to *E′* bears to the 365 days that the earth requires to complete its orbit. The angle *PSP′* can be determined in just the same way, since the time required by the planet to complete its orbit is already known, and the time occupied by the planet in going from *P* to *P′* is the same as that needed by the earth to go from *E* to *E′*. With *PSP′* and *ESE′* known, the angle *P′SE′* can be found by subtraction. Then we again have a right triangle, *SE′P′*, with one acute angle, *P′SE′*, known, and the ratio of the radius of the planet's orbit, *SP′*, to that of the earth's orbit, *SE′*, can therefore be determined just as for an inferior planet.

By techniques like this the distances to all the planets can be determined in terms of the distance between the earth and the sun, or in terms of any unit, like the stade, in which the radius of the earth's orbit has been measured. Now, for the first time, as Copernicus says in his prefatory letter, "the orders and magnitudes of all stars and spheres . . . become so bound together that nothing in any part thereof could be moved from its place without producing confusion of all the other parts and of the universe as a whole." Because the

relative dimensions of the planetary orbits are a direct consequence of the first geometric premises of sun-centered astronomy, the new astronomy has for Copernicus a naturalness and coherence that were lacking in the older earth-centered version. The structure of the heavens can be derived from Copernicus' system with fewer extraneous or *ad hoc* assumptions like plenitude. That is the new and aesthetic harmony which Copernicus emphasizes and illustrates so fully in the tenth chapter of his introductory First Book, to which we now turn, having first learned enough about the new system (as Copernicus' lay readers had not) to understand what he is talking about.

10. *Of the Order of the Heavenly Bodies.*

No one doubts that the Sphere of the Fixed Stars is the most distant of visible things. As for the order of the planets, the early Philosophers wished to determine it from the magnitude of their revolutions. They adduce the fact that of objects moving with equal speed, those farther distant seem to move more slowly (as is proved in Euclid's *Optics*). They think that the Moon describes her path in the shortest time because, being nearest to the Earth, she revolves in the smallest circle. Farthest they place Saturn, who in the longest time describes the greatest circuit. Nearer than he is Jupiter, and then Mars.

Opinions differ as to Venus and Mercury which, unlike the others, do not altogether leave the Sun. Some place them beyond the Sun, as Plato in *Timaeus*; others nearer than the Sun, as Ptolemy and many of the moderns. Alpetragius [a twelfth-century Moslem astronomer] makes Venus nearer and Mercury farther than the Sun. If we agree with Plato in thinking that the planets are themselves dark bodies that do but reflect light from the Sun, it must follow, that if nearer than the Sun, on account of their proximity to him they would appear as half or partial circles; for they would generally reflect such light as they receive upwards, that is toward the Sun, as with the waxing or waning Moon. [See the discussion of the phases of Venus in the next chapter. Neither this effect nor the following is distinctly visible without the telescope.] Some think that since no eclipse even proportional to their size is ever caused by these planets, they can never be between us and the Sun. . . . [Copernicus proceeds to note many difficulties in the arguments usually used to determine the relative order of the sun and the inferior planets. Then he continues:]

Unconvincing too is Ptolemy's proof that the Sun moves between those bodies that do and those that do not recede from him completely [that is, between the superior planets which can assume any angle of elongation and the inferior planets whose maximum elongation is limited]. Consideration of the case of the Moon, which does so recede, exposes its falseness. Again, what cause can be alleged, by those who place Venus nearer than the Sun, and Mercury next, or in some other order? Why should not these planets also follow separate paths, distinct from that of the Sun, as do the other planets [whose deferents are not tied to the sun's]? And this might be said even if their relative swiftness and slowness did not belie their alleged order. Either then the Earth cannot be the center to which the order of the planets and their Spheres is related, or certainly their relative order is not observed, nor does it appear why a higher position should be assigned to Saturn than to Jupiter, or any other planet.

Therefore I think we must seriously consider the ingenious view held by Martianus Capella [a Roman encyclopedist of the fifth century who recorded a theory of the inferior planets probably first suggested by Heraclides] . . . and certain other Latins, that Venus and Mercury do not go round the Earth like the other planets but run their courses with the Sun as center, and so do not depart from him farther than the convexity of their Spheres allows. . . . What else can they mean than that the center of these Spheres is near the Sun? So certainly the circle of Mercury must be within that of Venus, which, it is agreed, is more than twice as great.

We may now extend this hypothesis to bring Saturn, Jupiter and Mars also into relation with this center, making their Spheres great enough to contain those of Venus and Mercury and the Earth. . . . These outer planets are always nearer to the Earth about the time of their evening rising, that is, when they are in opposition to the Sun, and the Earth between them and the Sun. They are more distant from the Earth at the time of their evening setting, when they are in conjunction with the Sun and the Sun between them and the Earth. These indications prove that their center pertains rather to the Sun than to the Earth, and that this is the same center as that to which the revolutions of Venus and Mercury are related.

[Copernicus' remarks do not actually "prove" a thing. The Ptolemaic system explains these phenomena as completely as the Copernican, but the Copernican explanation is again more natural, for, like the Copernican explanation of the limited elongation of the inferior planets, it depends only on the geometry of a sun-centered astronomical system, not on the particular orbital periods assigned to the planets. Copernicus' remarks will be clarified by reference to Figure 32*a*. A superior planet retrogresses when the earth overtakes it, and under these circumstances it must be simultaneously closest to the earth and across the ecliptic from the sun. In the Ptolemaic system a retrogressing superior planet must be closer to the earth than at any other time, and it is in fact also across the sky from the sun. But it is only across the sky from the sun because the rates of rotation of its deferent and epicycle have particular values that happen to put the planet back in opposition to the sun whenever the epicycle brings the planet back close to the central earth. If, in the Ptolemaic system, the period of epicycle or deferent were quantitatively slightly different, then the qualitative regularity that puts a retrogressing superior planet across the sky from the sun would not occur. In the Copernican system it must occur regardless of the particular rates at which the planets revolve in their orbits.]

But since all these [Spheres] have one center it is necessary that the space between the convex side of Venus's Sphere and the concave side of Mars's must also be viewed as a Sphere concentric with the others, capable of receiving the Earth with her satellite the Moon and whatever is contained within the Sphere of the Moon – for we must not separate the Moon from the Earth, the former being beyond all doubt nearest to the latter, especially as in that space we find suitable and ample room for the Moon.

We therefore assert that the center of the Earth, carrying the Moon's path, passes in a great circuit among the other planets in an annual revolution round the Sun; that near the Sun is the center of the Universe; and that whereas the Sun is at rest, any apparent motion of the Sun can be better explained by motion of the Earth. Yet so great is the Universe that though the distance of the Earth from the Sun is not insignificant compared with the size of any other planetary path, in accordance with the ratios of their sizes, it is insignificant compared with the distances of the Sphere of the Fixed Stars.

I think it easier to believe this than to confuse the issue by assuming a vast number of Spheres, which those who keep Earth at the center must do. We thus rather follow Nature, who producing nothing vain or superfluous often prefers to endow one cause with many effects. Though these views are difficult, contrary to expectation, and certainly unusual, yet in the sequel we shall, God willing, make them abundantly clear at least to mathematicians.

Given the above view – and there is none more reasonable – that the periodic times are proportional to the sizes of the Spheres, then the order of the Spheres, beginning from the most distant is as follows. Most distant of all is the Sphere of the Fixed Stars, containing all things, and being therefore itself immovable. It represents that to which the motion and position of all the other bodies must be referred . . . . Next is the planet Saturn, revolving in 30 years. Next comes Jupiter, moving in a 12-year circuit; then Mars, who goes round in 2 years. The fourth place is held by the annual revolution [of the Sphere] in which the Earth is contained, together with the Sphere of the Moon as on an epicycle. Venus, whose period is 9 months, is in the fifth place, and sixth is Mercury, who goes round in the space of 80 days.

In the middle of all sits Sun enthroned. In this most beautiful temple could we place this luminary in any better position from which he can illuminate the whole at once? He is rightly called the Lamp, the Mind, the

Ruler of the Universe; Hermes Trismegistus names him the Visible God, Sophocles' Electra calls him the All-seeing. So the Sun sits as upon a royal throne ruling his children the planets which circle round him. The Earth has the Moon at her service. As Aristotle says, in his *On [the Generation of] Animals*, the Moon has the closest relationship with the Earth. Meanwhile the Earth conceives by the Sun, and becomes pregnant with an annual rebirth.

So we find underlying this ordination an admirable symmetry in the Universe, and a clear bond of harmony in the motion and magnitude of the Spheres such as can be discovered in no other wise. For here we may observe why the progression and retrogression appear greater for Jupiter than Saturn, and less than for Mars, but again greater for Venus than for Mercury [a glance at Figure 32 will show that the closer the orbit of a planet is to the orbit of the earth, the larger the apparent retrograde motion of that planet must be – an additional harmony of Copernicus' system]; and why such oscillation appears more frequently in Saturn than in Jupiter, but less frequently in Mars and Venus than in Mercury [the earth will lap a slowly moving superior planet more frequently than it laps a rapid one, and conversely for an inferior planet]; moreover why Saturn, Jupiter and Mars are nearer to the Earth at opposition to the Sun than when they are lost in or emerge from the Sun's rays. Particularly Mars, when he shines all night [and is therefore in opposition], appears to rival Jupiter in magnitude, being only distinguishable by his ruddy color; otherwise he is scarce equal to a star of the second magnitude, and can be recognized only when his movements are carefully followed. All these phenomena proceed from the same cause, namely Earth's motion.

That there are no such phenomena for the fixed stars proves their immeasurable distance, because of which the outer sphere's [apparent] annual motion or its [parallactic] image is invisible to the eyes. For every visible object has a certain distance beyond which it can no more be seen, as is proved in optics. The twinkling of the stars, also, shows that there is still a vast distance between the farthest of the planets, Saturn, and the Sphere of the Fixed Stars [for if the stars were very near Saturn, they should shine as he does], and it is chiefly by this indication that they are distinguished from the planets. Further, there must necessarily be a great difference between moving and non-moving bodies. So great is this divine work of the Great and Noble Creator!

Throughout this crucially important tenth chapter Copernicus' emphasis is upon the "admirable symmetry" and the "clear bond of harmony in the motion and magnitude of the Spheres" that a sun-centered geometry imparts to the appearances of the heavens. If the sun is the center, then an inferior planet cannot possibly appear far from the sun; if the sun is the center, then a superior planet must be

in opposition to the sun when it is closest to the earth; and so on and on. It is through arguments like these that Copernicus seeks to persuade his contemporaries of the validity of his new approach. Each argument cites an aspect of the appearances that can be explained by *either* the Ptolemaic *or* the Copernican system, and each then proceeds to point out how much more harmonious, coherent, and natural the Copernican explanation is. There are a great many such arguments. The sum of the evidence drawn from harmony is nothing if not impressive.

But it may well be nothing. "Harmony" seems a strange basis on which to argue for the earth's motion, particularly since the harmony is so obscured by the complex multitude of circles that make up the full Copernican system. Copernicus' arguments are not pragmatic. They appeal, if at all, not to the utilitarian sense of the practicing astronomer but to his aesthetic sense and to that alone. They had no appeal to laymen, who, even when they understood the arguments, were unwilling to substitute minor celestial harmonies for major terrestrial discord. They did not necessarily appeal to astronomers, for the harmonies to which Copernicus' arguments pointed did not enable the astronomer to perform his job better. New harmonies did not increase accuracy or simplicity. Therefore they could and did appeal primarily to that limited and perhaps irrational subgroup of mathematical astronomers whose Neoplatonic ear for mathematical harmonies could not be obstructed by page after page of complex mathematics leading finally to numerical predictions scarcely better than those they had known before. Fortunately, as we shall discover in the next chapter, there were a few such astronomers. Their work is also an essential ingredient of the Copernican Revolution.

Revolution by Degrees

Because he was the first fully to develop an astronomical system based upon the motion of the earth, Copernicus is frequently called the first modern astronomer. But, as the text of the *De Revolutionibus* indicates, an equally persuasive case might be made for calling him the last great Ptolemaic astronomer. Ptolemaic astronomy meant far more than astronomy predicated on a stationary earth, and it is only with respect to the position and motion of the earth that Copernicus broke with the Ptolemaic tradition. The cosmological frame in which his astronomy was embedded, his physics, terrestrial and celestial, and even the mathematical devices that he employed to make his system give adequate predictions are all in the tradition established by ancient and medieval scientists.

Though historians have occasionally grown livid arguing whether Copernicus is really the last of the ancient or the first of the modern astronomers, the debate is in principle absurd. Copernicus is neither an ancient nor a modern but rather a Renaissance astronomer in whose work the two traditions merge. To ask whether his work is really ancient or modern is rather like asking whether the bend in an otherwise straight road belongs to the section of road that precedes the bend or to the portion that comes after it. From the bend both sections of the road are visible, and its continuity is apparent. But viewed from a point before the bend, the road seems to run straight to the bend and then to disappear; the bend seems the last point in a straight road. And viewed from a point in the next section, after the bend, the road appears to begin at the bend from which it runs straight on. The bend belongs equally to both sections, or it belongs to neither. It marks a turning point in the direction of the road's progress, just as the *De Revolutionibus* marks a shift in the direction in which astronomical thought developed.

To this point in this chapter we have emphasized primarily the ties between the *De Revolutionibus* and the earlier astronomical and cosmological tradition. We have minimized, as Copernicus himself does, the extent of the Copernican innovation, because we have been concerned to discover how a potentially destructive innovation could be produced by the tradition that it was ultimately to destroy. But, as we shall soon discover, this is not the only legitimate way to view the *De Revolutionibus*, and it is not the view taken by most later Copernicans. For Copernicus' sixteenth- and seventeenth-century followers, the primary importance of the *De Revolutionibus* derived from its single novel concept, the planetary earth, and from the novel astronomical consequences, the new harmonies, which Copernicus had derived from that concept. To them Copernicanism meant the threefold motion of the earth and, initially, that alone. The traditional conceptions with which Copernicus had clothed his innovation were not to his followers essential elements of his work, simply because, as traditional elements, they were not Copernicus' contribution to science. It was not because of its traditional elements that people quarreled about the *De Revolutionibus*.

That is why the *De Revolutionibus* could be the starting point for a new astronomical and cosmological tradition as well as the culmination of an old one. Those whom Copernicus converted to the concept of a moving earth began their research from the point at which Copernicus had stopped. Their starting point was the earth's motion, which was all they necessarily took from Copernicus, and the problems to which they devoted themselves were not the problems of the old astronomy, which had occupied Copernicus, but the problems of the new sun-centered astronomy, which they discovered in the *De Revolutionibus*. Copernicus presented them with a set of problems that neither he nor his predecessors had had to face. In the pursuit of those problems the Copernican Revolution was completed, and a new astronomical tradition, deriving from the *De Revolutionibus*, was founded. Modern astronomy looks back to the *De Revolutionibus* as Copernicus had looked back to Hipparchus and Ptolemy.

Major upheavals in the fundamental concepts of science occur by degrees. The work of a single individual may play a preëminent role in such a conceptual revolution, but if it does, it achieves preëminence either because, like the *De Revolutionibus*, it initiates revolution by a small innovation which presents science with new problems, or because, like Newton's *Principia*, it terminates revolution by integrating concepts derived from many sources. The extent of the innovation that any individual can produce is necessarily limited, for each individual must employ in his research the tools that he acquires from a traditional education, and he cannot in his own lifetime replace them all. It seems therefore that many of the elements in the *De Revolutionibus* which, in the earlier parts of this chapter, we pointed to as incongruities are not really incongruities at all. The *De Revolutionibus* seems incongruous only to those who expect to find the entire Copernican Revolution in the work which gives that revolution its name, and such an expectation derives from a misunderstanding of the way in which new patterns of scientific thought are produced. The limitations of the *De Revolutionibus* might better be regarded as essential and typical characteristics of any revolution-making work.

Most of the apparent incongruities in the *De Revolutionibus* reflect the personality of its author, and Copernicus' personality seems entirely appropriate to his seminal role in the development of astronomy. Copernicus was a dedicated specialist. He belonged to the revived Hellenistic tradition of mathematical astronomy which emphasized the mathematical problem of the planets at the expense of cosmology. For his Hellenistic predecessors the physical incongruity of an epicycle had not been an important drawback of the Ptolemaic system, and Copernicus displayed a similar indifference to cosmological detail when he failed to note the incongruities of a moving earth in an otherwise traditional universe. For him, mathematical and celestial detail came first; he wore blinders that kept his gaze focused upon the mathematical harmonies of the heavens. To anyone who did not share his specialty Copernicus' view of the universe was narrow and his sense of values distorted.

But an excessive concern with the heavens and a distorted sense of values may be essential characteristics of the man who inaugurated the revolution in astronomy and cosmology. The blinders that restricted Copernicus' gaze to the heavens may have been functional. They made him so perturbed by discrepancies of a few degrees in astronomical prediction that in an attempt to resolve them he could embrace a cosmological heresy, the earth's motion. They gave him an eye so absorbed with geometrical harmony that he could adhere to his heresy for its harmony alone, even when it had failed to solve the problem that had led him to it. And they helped him evade the nonastronomical consequences of his innovation, consequences that led men of less restricted vision to reject his innovation as absurd.

Above all, Copernicus' dedication to the celestial motions is responsible for the painstaking detail with which he explored the mathematical consequences of the earth's motion and fitted those consequences to an existing knowledge of the heavens. That detailed technical study is Copernicus' real contribution. Both before and after Copernicus there were cosmologists more radical than he, men who with broad brush strokes sketched an infinite and multipopulated universe. But none of them produced work resembling the later books of the *De Revolutionibus*, and it is these books which, by showing for the first time that the astronomer's job could be done, and done more harmoniously, from a moving earth, provided a stable base from which to launch a new astronomical tradition. Had Copernicus' cosmological First Book appeared alone, the Copernican Revolution would and should be known by someone else's name.

6

THE ASSIMILATION OF COPERNICAN ASTRONOMY

The Reception of Copernicus' Work

Copernicus died in 1543, the year in which the *De Revolutionibus* was published, and tradition tells us that he received the first printed copy of his life's work on his deathbed. The book had to fight its battles without further help from its author. But for those battles Copernicus had constructed an almost ideal weapon. He had made the book unreadable to all but the erudite astronomers of his day. Outside of the astronomical world the *De Revolutionibus* created initially very little stir. By the time large-scale lay and clerical opposition developed, most of the best European astronomers, to whom the book was directed, had found one or another of Copernicus' mathematical techniques indispensable. It was then impossible to suppress the work completely, particularly because it was in a printed book and not, like Oresme's work or Buridan's, in a manuscript. Whether intentionally or not, the final victory of the *De Revolutionibus* was achieved by infiltration.

For two decades before the publication of his principal work Copernicus had been widely recognized as one of Europe's leading astronomers. Reports about his research, including his new hypothesis, had circulated since about 1515. The publication of the *De Revolutionibus* was eagerly awaited. When it appeared, Copernicus' contemporaries may have been skeptical of its main hypothesis and disappointed in the complexity of its astronomical theory, but they were nevertheless forced to recognize Copernicus' book as the first European astronomical text that could rival the *Almagest* in depth and completeness. Many advanced astronomical texts written during the fifty years after Copernicus' death referred to him as a "second