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THE ANCIENT TWO-SPHERE UNIVERSE

Copernicus and the Modern Mind

The Copernican Revolution was a revolution in ideas, a transformation in man's conception of the universe and of his own relation to it. Again and again this episode in the history of Renaissance thought has been proclaimed an epochal turning point in the intellectual development of Western man. Yet the Revolution turned upon the most obscure and recondite minutiae of astronomical research. How can it have had such significance? What does the phrase "Copernican Revolution" mean?

In 1543, Nicholas Copernicus proposed to increase the accuracy and simplicity of astronomical theory by transferring to the sun many astronomical functions previously attributed to the earth. Before his proposal the earth had been the fixed center about which astronomers computed the motions of stars and planets. A century later the sun had, at least in astronomy, replaced the earth as the center of planetary motions, and the earth had lost its unique astronomical status, becoming one of a number of moving planets. Many of modern astronomy's principal achievements depend upon this transposition. A reform in the fundamental concepts of astronomy is therefore the first of the Copernican Revolution's meanings.

Astronomical reform is not, however, the Revolution's only meaning. Other radical alterations in man's understanding of nature rapidly followed the publication of Copernicus' *De Revolutionibus* in 1543. Many of these innovations, which culminated a century and a half later in the Newtonian conception of the universe, were unanticipated by-products of Copernicus' astronomical theory. Copernicus suggested the earth's motion in an effort to improve the techniques used in predicting the astronomical positions of celestial bodies. For other sciences his suggestion simply raised new problems, and until these were solved the astronomer's concept of the universe was incompatible with that of other scientists. During the seventeenth century, the reconciliation of these other sciences with Copernican astronomy was an important cause of the general intellectual ferment now known as the scientific revolution. Through the scientific revolution science won the great new role that it has since played in the development of Western society and Western thought.

Even its consequences for science do not exhaust the Revolution's meanings. Copernicus lived and worked during a period when rapid changes in political, economic, and intellectual life were preparing the bases of modern European and American civilization. His planetary theory and his associated conception of a sun-centered universe were instrumental in the transition from medieval to modern Western society, because they seemed to affect man's relation to the universe and to God. Initiated as a narrowly technical, highly mathematical revision of classical astronomy, the Copernican theory became one focus for the tremendous controversies in religion, in philosophy, and in social theory, which, during the two centuries following the discovery of America, set the tenor of the modern mind. Men who believed that their terrestrial home was only a planet circulating blindly about one of an infinity of stars evaluated their place in the cosmic scheme quite differently than had their predecessors who saw the earth as the unique and focal center of God's creation. The Copernican Revolution was therefore also part of a transition in Western man's sense of values.

This book is the story of the Copernican Revolution in all three of these not quite separable meanings – astronomical, scientific, and philosophical. The Revolution as an episode in the development of planetary astronomy will, of necessity, be our most developed theme. During the first two chapters, as we discover what the naked eye can see in the heavens and how stargazers first reacted to what they saw there, astronomy and astronomers will be very nearly our only concern. But once we have examined the main astronomical theories developed in the ancient world, our viewpoint will shift. In analyzing the strengths of the ancient astronomical tradition and in exploring the requisites for a radical break with that tradition, we shall gradually discover how difficult it is to restrict the scope of an established scientific concept to a single science or even to the sciences as a group. Therefore, in

Chapters 3 and 4 we shall be less concerned with astronomy itself than with the intellectual and, more briefly, the social and economic milieu within which astronomy was practiced. These chapters will deal primarily with the extra-astronomical implications – for science, for religion, and for daily life – of a time-honored astronomical conceptual scheme. They will show how a change in the conceptions of mathematical astronomy could have revolutionary consequences. Finally, in the last three chapters, when we turn to Copernicus' work, its reception, and its contribution to a new scientific conception of the universe, we shall deal with all these strands at once. Only the battle that established the concept of the planetary earth as a premise of Western thought can adequately represent the full meaning of the Copernican Revolution to the modern mind.

Because of its technical and historical outcome, the Copernican Revolution is among the most fascinating episodes in the entire history of science. But it has an additional significance which transcends its specific subject: it illustrates a process that today we badly need to understand. Contemporary Western civilization is more dependent, both for its everyday philosophy and for its bread and butter, upon scientific concepts than any past civilization has been. But the scientific theories that bulk so large in our daily lives are unlikely to prove final. The developed astronomical conception of a universe in which the stars, including our sun, are scattered here and there through an infinite space is less than four centuries old, and it is already out of date. Before that conception was developed by Copernicus and his successors, other notions about the structure of the universe were used to explain the phenomena that man observed in the heavens. These older astronomical theories differed radically from the ones we now hold, but most of them received in their day the same resolute credence that we now give our own. Furthermore, they were believed for the same reasons: they provided plausible answers to the questions that seemed important. Other sciences offer parallel examples of the transiency of treasured scientific beliefs. The basic concepts of astronomy have, in fact, been more stable than most.

The mutability of its fundamental concepts is not an argument for rejecting science. Each new scientific theory preserves a hard core of the knowledge provided by its predecessor and adds to it. Science progresses by replacing old theories with new. But an age as dominated by science as our own does need a perspective from which to examine the scientific beliefs which it takes so much for granted, and history provides one important source of such perspective. If we can discover the origins of some modern scientific concepts and the way in which they supplanted the concepts of an earlier age, we are more likely to evaluate intelligently their chances for survival. This book deals primarily with astronomical concepts, but they are much like those employed in many other sciences, and by scrutinizing their development we can learn something of scientific theories in general. For example: What is a scientific theory? On what should it be based to command our respect? What is its function, its use? What is its staying power? Historical analysis may not answer questions like these, but it can illuminate them and give them meaning.

Because the Copernican theory is in many respects a typical scientific theory, its history can illustrate some of the processes by which scientific concepts evolve and replace their predecessors. In its extrascientific consequences, however, the Copernican theory is not typical: few scientific theories have played so large a role in nonscientific thought. But neither is it unique. In the nineteenth century, Darwin's theory of evolution raised similar extrascientific questions. In our own century, Einstein's relativity theories and Freud's psychoanalytic theories provide centers for controversies from which may emerge further radical reorientations of Western thought. Freud himself emphasized the parallel effects of Copernicus' discovery that the earth was merely a planet and his own discovery that the unconscious controlled much of human behavior. Whether we have learned their theories or not, we are the intellectual heirs of men like Copernicus and Darwin. Our fundamental thought processes have been reshaped by them, just as the thought of our children or grandchildren will have been reshaped by the work of Einstein and Freud. We need more than an understanding of the internal development of science. We must also understand how a scientist's solution of an apparently petty, highly technical problem can on occasion fundamentally alter men's attitudes toward basic problems of everyday life.

The Heavens in Primitive Cosmologies

Much of this book will deal with the impact of astronomical observations and theories upon ancient and early modern cosmological thought, that is, upon a set of man's conceptions about the structure of the universe. Today we take it for granted that astronomy should affect

cosmology. If we want to know the shape of the universe, the earth's position in it, or the relation of the earth to the sun and the sun to the stars, we ask the astronomer or perhaps the physicist. They have made detailed quantitative observations of the heavens and the earth; their knowledge of the universe is guaranteed by the accuracy with which they predict its behavior. Our everyday conception of the universe, our popular cosmology, is one product of their painstaking researches. But this close association of astronomy and cosmology is both temporally and geographically local. Every civilization and culture of which we have records has had an answer for the question, "What is the structure of the universe?" But only the Western civilizations which descend from Hellenic Greece have paid much attention to the appearance of the heavens in arriving at that answer. The drive to construct cosmologies is far older and more primitive than the urge to make systematic observations of the heavens. Furthermore, the primitive form of the cosmological drive is particularly informative because it highlights features obscured in the more technical and abstract cosmologies that are familiar today.

Though primitive conceptions of the universe display considerable substantive variation, all are shaped primarily by terrestrial events, the events that impinge most immediately upon the designers of the systems. In such cosmologies the heavens are merely sketched in to provide an enclosure for the earth, and they are peopled with and moved by mythical figures whose rank in the spiritual hierarchy usually increases with their distance from the immediate terrestrial environment. For example, in one principal form of Egyptian cosmology the earth was pictured as an elongated platter. The platter's long dimension paralleled the Nile; its flat bottom was the alluvial basin to which ancient Egyptian civilization was restricted; and its curved and rippled rim was the mountains bounding the terrestrial world. Above the platter-earth was air, itself a god, supporting an inverted platter-dome which was the skies. The terrestrial platter in its turn was supported by water, another god, and the water rested upon a third platter which bounded the universe symmetrically from below.

Clearly several of the main structural features of this universe were suggested by the world that the Egyptian knew: he did live in an elongated platter bounded by water in the only direction in which he had explored it; the sky, viewed on a clear day or night, did and does look dome-shaped; a symmetric lower boundary for the universe was the obvious choice in the absence of relevant observations. Astronomical appearances were not ignored, but they were treated with less precision and more myth. The sun was Ra, the principal Egyptian god, supplied with two boats, one for his daily journey through the air and a second for his nocturnal trip through the water. The stars were painted or studded in the vault of the heaven; they moved as minor gods; and in some versions of the cosmology they were reborn each night. Sometimes more detailed observations of the heavens entered, as when the circumpolar stars (stars that never dip below the horizon) were recognized as "those that know no weariness" or "those that know no destruction." From such observations the northern heavens were identified as a region where there could be no death, the region of the eternally blessed afterlife. But such traces of celestial observation were rare.

Fragments of cosmologies similar to the Egyptian can be found in all those ancient civilizations, like India and Babylonia, of which we have records. Other crude cosmologies characterize the contemporary primitive societies investigated by the modern anthropologist. Apparently all such sketches of the structure of the universe fulfill a basic psychological need: they provide a stage for man's daily activities and the activities of his gods. By explaining the physical relation between man's habitat and the rest of nature, they integrate the universe for man and make him feel at home in it. Man does not exist for long without inventing a cosmology, because a cosmology can provide him with a world-view which permeates and gives meaning to his every action, practical and spiritual.

Though the psychological needs satisfied by a cosmology seem relatively uniform, the cosmologies capable of fulfilling these needs have varied tremendously from one society or civilization to another. None of the primitive cosmologies referred to above will now satisfy our demand for a world-view, because we are members of a civilization that has set additional standards which a cosmology must meet in order to be believed. We will not, for example, credit a cosmology that employs gods to explain the everyday behavior of the physical world; in recent centuries, at least, we have insisted upon more nearly mechanical explanations. Even more important, we now demand that a satisfactory cosmology account for many of the observed details of nature's behavior. Primitive cosmologies are only schematic sketches against

which the play of nature takes place; very little of the play is incorporated into the cosmology. The sun god, Ra, travels in his boat across the heavens each day, but there is nothing in Egyptian cosmology to explain either the regular recurrence of his journey or the seasonal variation of his boat's route. Only in our own Western civilization has the explanation of such details been considered a function of cosmology. No other civilization, ancient or modern, has made a similar demand.

The requirement that a cosmology supply *both* a psychologically satisfying world-view *and* an explanation of observed phenomena like the daily change in the position of sunrise has vastly increased the power of cosmologic thought. It has channeled the universal compulsion for at-homeness in the universe into an unprecedented drive for the discovery of scientific explanations. Many of the most characteristic achievements of Western civilization depend upon this combination of demands imposed upon cosmologic thought. But the combination has not always been a congenial one. It has forced modern man to delegate the construction of cosmologies to specialists, primarily to astronomers, who know the multitude of detailed observations that modern cosmologies must satisfy to be believed. And since observation is a two-edged sword which may either confirm or conflict with a cosmology, the consequences of this delegation can be devastating. The astronomer may on occasions destroy, for reasons lying entirely within his specialty, a world-view that had previously made the universe meaningful for the members of a whole civilization, specialist and nonspecialist alike.

Something very much like this happened during the Copernican Revolution. To understand it we must therefore become something of specialists ourselves. In particular, we must get to know the principal observations, all of them accessible to the naked eye, upon which depend the two main scientific cosmologies of the West, the Ptolemaic and the Copernican. No single panoramic view of the heavens will suffice. Seen on a clear night, the skies speak first to the poetic, not to the scientific, imagination. No one who views the night sky can challenge Shakespeare's vision of the stars as "night's candles" or Milton's image of the Milky Way as "a broad and ample road, whose dust is gold, and pavement stars." But these descriptions are the ones embodied in primitive cosmologies. They provide no evidence relevant to the astronomer's questions: How far away is the Milky Way, the sun, the planet Jupiter? How do these points of light move? Is the material of the moon like the earth's, or is it like the sun's, or like a star's? Questions like these demand systematic, detailed, and quantitative observations accumulated over a long period of time.

This chapter deals, then, with observations of the sun and stars and with the role of these observations in establishing the first scientific cosmologies of ancient Greece. The next chapter completes the roster of naked-eye celestial observations by describing the planets, the celestial bodies which posed the technical problem that led to the Copernican Revolution.

The Apparent Motion of the Sun

Before the end of the second millennium B.C. (perhaps very much before), the Babylonians and the Egyptians had begun systematic observations of the motion of the sun. For this purpose they developed a primitive sundial consisting of a measured stick, the gnomon, projecting vertically from a smooth flat section of ground. Since the apparent position of the sun, the tip of the gnomon, and the tip of its shadow lie along a straight line at each instant of a clear day, measurements of the length and direction of the shadow completely determine the direction of the sun. When the shadow is short, the sun is high in the sky; when the shadow points, say, to the east, the sun must lie in the west. Repeated observations of the gnomon's shadow can therefore systematize and quantify a vast amount of common but vague knowledge about the daily and annual variation of the sun's position. In antiquity such observations harnessed the sun as a time reckoner and calendar keeper, applications that provided one important motive for continuing and refining the observational techniques.

Both the length and the direction of a gnomon's shadow vary slowly and continuously during the course of any one day. The shadow is longest at sunrise and sunset, at which times it points in roughly opposite directions. During the daylight hours the shadow moves gradually through a symmetric fan-shaped figure which, in most of the locations accessible to ancient observers, is much like one of those shown in Figure 1. As the diagram indicates, the shape of the fan is different on different days, but it has one very significant fixed feature. At the instant of each day when the gnomon's shadow is shortest, it always points in the same direction. This simple regularity provides

two fundamental frames of reference for all further astronomical measurements. The permanent direction assumed by the shortest shadow each day defines due north, from which the other compass points follow; the instant at which the shadow becomes shortest defines a reference point in time, local noon; and the interval between two successive local noons defines a fundamental time unit, the apparent solar day. During the first millennium B.C., the Babylonians, Egyptians, Greeks, and Romans used primitive terrestrial timekeepers, particularly water clocks, in order to subdivide the solar day into smaller intervals from which our modern units of time – hour, minute, and second – descend.*

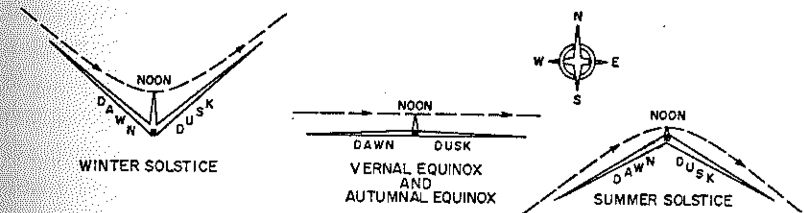


Figure 1. The daily motion of the gnomon's shadow at various seasons in middle-northern latitudes. At sunrise and sunset the shadow stretches momentarily to infinite distance where its end "joins" the broken line in the diagram. Between sunrise and sunset the end of the shadow moves slowly along the broken line; at noon the shadow always points due north.

The compass points and the time units defined by the sun's daily motion provide a basis for describing the changes in that motion from day to day. Sunrise always occurs somewhere in the east and sunset in the west, but the position of sunrise, the length of the gnomon's noon shadow, and the number of daylight hours vary from day to day with the changing seasons (Figure 2). The winter solstice is the day (December 22 on the modern calendar) when the sun rises and sets farthest to the south of the due east and west points on the horizon. On this day there are fewer hours of daylight and the gnomon's noon shadow is longer than on any other. After the winter solstice the points

* For astronomical purposes the stars provide a more convenient time reckoner than the sun. But, on a time scale determined by the stars, the length of the apparent solar day varies by almost a minute at different seasons of the year. Though ancient astronomers were aware of this slight but significant irregularity of apparent solar time, we shall ignore it here. The cause of this variation and its effect upon the definition of a time scale are discussed in Section 1 of the Technical Appendix.

at which the sun rises and sets gradually move north together along the horizon, and the noon shadows grow shorter. On the vernal equinox (March 21) the sun rises and sets most nearly due east and west; nights and days are then of equal length. As more days pass, the sunrise and sunset points continue to move northward and the number of daylight hours increases until the summer solstice (June 22), when the sun rises and sets farthest to the north. This is the time when daylight lasts longest and when the gnomon's noon shadow is shortest. After the summer solstice, the sunrise point again moves south, and the nights grow longer. At the autumnal equinox (September 23) the sun once again rises and sets almost due east and west; then it continues south until the winter solstice recurs.

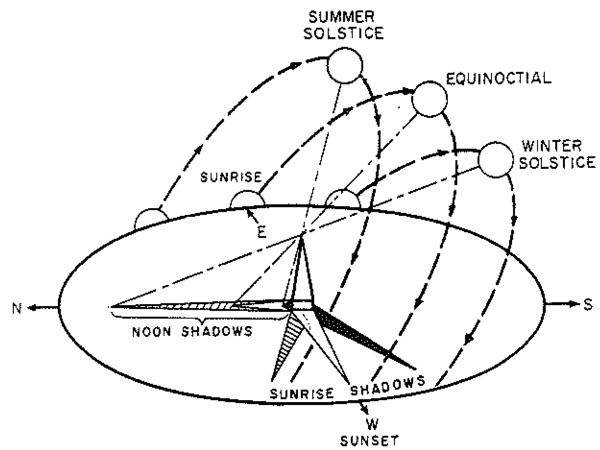


Figure 2. Relation between the position of sunrise, the sun's noon elevation, and the seasonal variation of the gnomon's shadow.

As the modern names of the solstices and equinoxes indicate, the motion of sunrise back and forth along the horizon corresponds to the cycle of the seasons. Most ancient peoples therefore believed that the sun controlled the seasons. They simultaneously venerated the sun as a god and observed it as a calendar keeper, a practical indicator of the passage of the seasons upon which their agricultural activities depended. Prehistoric remains, like the mysterious structure of giant stones at Stonehenge, England, testify to the antiquity and the strength of this double interest in the sun. Stonehenge was an important temple

laboriously constructed from huge stones, some almost thirty tons in weight, by the people of an early Stone Age civilization. It was almost certainly also a crude sort of observatory. The stones were so arranged that an observer at the center of the array saw the sun rise over a specially placed stone, called the "Friar's Heel," on the ancient midsummer day, the summer solstice.

The length of the cycle of the seasons – the interval between one vernal equinox and the next – defines the basic calendar unit, the year, just as the sun's daily motion defines the day. But the year is a far more difficult unit to measure than the day, and the demand for useful long-term calendars has therefore presented astronomers with a continuing problem whose prominence during the sixteenth century played a direct role in the Copernican Revolution. The earliest solar calendars of antiquity were based upon a year of 360 days, a neat round number that nicely fitted the sexagesimal number system of the Babylonians. But the cycle of the seasons occupies more than 360 days, so that the "New Year's Day" of these early solar calendars gradually crept around the cycle of the seasons from winter, to fall, to summer, to spring. The calendar was scarcely useful over long periods of time, because important seasonal events, like the flooding of the Nile in Egypt, occurred at later and later dates in successive years. To keep the solar calendar in step with the seasons, the Egyptians therefore added five extra days, a holiday season, to their original year.

There is, however, no integral number of days in the cycle of the seasons. The year of 365 days is also too short, and after 40 years the Egyptian calendar was ten days out of step with the seasons. Therefore, when Julius Caesar reformed the calendar with technical assistance from Egyptian astronomers, he based his new calendar upon a year 365¼ days in length; three years of 365 days were followed by one of 366. This calendar, the Julian, was used throughout Europe from its introduction in 45 B.C. until after the death of Copernicus. But the seasonal year is actually 11 minutes and 14 seconds shorter than 365¼ days, so that by Copernicus' lifetime the date of the vernal equinox had moved backward from March 21 to March 11. The resulting demand for calendar reform (see Chapters 4 and 5) provided one important motive for the reform of astronomy itself, and the reform that gave the Western world its modern calendar followed the publication of the *De Revolutionibus* by only thirty-nine years. In the new calendar, imposed upon large areas of Christian Europe by Pope Gregory XIII in 1582, leap year is suppressed three times in every four hundred years. The year 1600 was a leap year and the year 2000 will be, but 1700, 1800, and 1900, all leap years in the Julian calendar, had just 365 days in the Gregorian, and 2100 will again be a normal year of 365 days.

All the observations discussed above show the sun approximately as it would appear to an astronomer in middle-northern latitudes, an area that includes Greece, Mesopotamia, and northern Egypt, the regions in which almost all ancient observations were made. But within this area there is a considerable quantitative variation in certain aspects of the sun's behavior, and in the southernmost parts of Egypt there is a qualitative change as well. Knowledge of these changes also played a part in the construction of ancient astronomical theories. No variations are observed as an observer moves east or west. But toward the south the noon shadow of the gnomon is shorter and the noon sun higher in the sky than they would be on the same day in the north. Similarly, though the length of the whole day remains constant, the difference between the lengths of daytime and nighttime is smaller in the southern portion of middle-northern latitudes. Also, in this region the sun does not swing quite so far north and south along the horizon

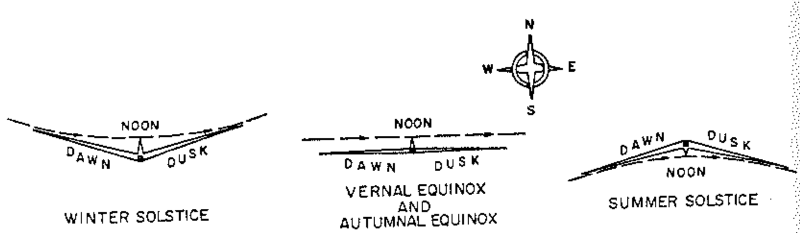


Figure 3. The daily motion of the gnomon's shadow at various seasons in the northern torrid zone.

during the course of the year. None of these variations alters the qualitative descriptions supplied above. But, if an observer has moved far into southern Egypt during the summer, he will see the noon shadow of the gnomon grow shorter day by day until at last it vanishes entirely and then reappears pointing to the south. In the southernmost parts of Egypt the annual behavior of the gnomon's shadow is that shown in Figure 3. Journeys still farther south or much farther north

will produce other anomalies in the observed motions of the sun. But these were not observed in antiquity. We shall not discuss them until we deal with the astronomical theories that made it possible to predict them even before they were observed (pp. 33 ff).

The Stars

The motions of the stars are much simpler and more regular than the sun's. Their regularity is not, however, so easily recognized because systematic examination of the night sky requires the ability to select individual stars for repeated study wherever in the heavens they appear. In the modern world this ability, which can be acquired only by long practice, is quite rare. Few people now spend much time out of doors at night, and, when they do, their view of the heavens is frequently obscured by tall buildings and street lighting. Besides, observation of the heavens no longer has a direct role in the life of the average man. But in antiquity the stars were an immediate part of the normal man's environment, and celestial bodies served a universal function as time reckoners and calendar keepers. Under these circum-

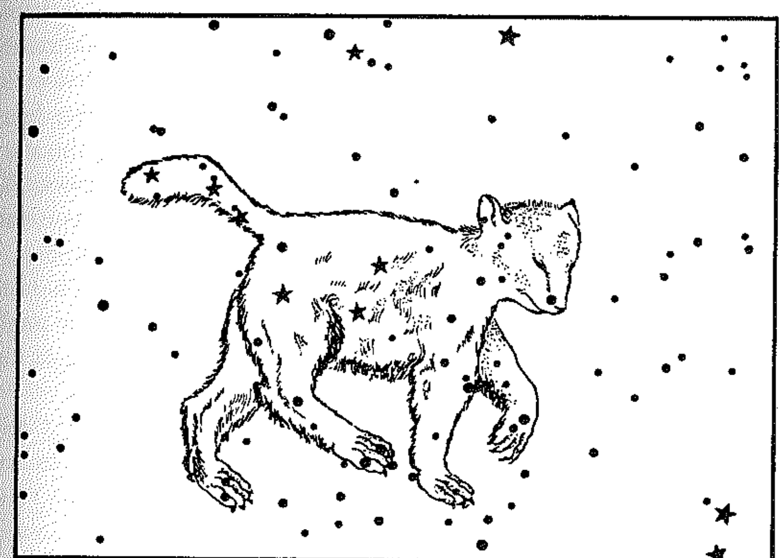


Figure 4. The constellation Ursa Major in the northern skies. Notice the familiar Big Dipper whose handle forms the bear's tail. The North Star is the prominent star directly over the bear's right ear in the picture. It lies almost on a line joining the last two stars in the Dipper's bowl.

stances the ability to identify stars at a glance was relatively common. Long before the beginning of recorded history men whose jobs gave them a continuing view of the night sky had mentally arranged the stars into constellations, groups of neighboring stars that could be seen and recognized as a fixed pattern. To find an individual star amidst the profusion of the heavens, an observer would first locate the familiar star pattern within which it occurred and then pick the individual star from the pattern.

Many of the constellations used by modern astronomers are named after mythological figures of antiquity. Some can be traced to Babylonian cuneiform tablets, a few as old as 3000 B.C. Though modern astronomy has modified their definitions, the major constellations are among our oldest traceable inheritances. How these groups were first picked out is, however, still uncertain. Few people can "see" a bear in the stars of the constellation Ursa Major (Figure 4); other constellations present similar problems in visualization; the stars may therefore originally have been grouped for convenience and named arbitrarily. But, if so, they were very strangely grouped. The ancient constellations have very irregular boundaries, and they occupy areas of quite different size in the sky. They are not convenient choices, which is one reason why modern astronomers have altered their boundaries. Probably the ancient shepherd or navigator, staring at the heavens hour after hour, really did "see" his familiar mythological characters traced in the stars, just as we sometimes "see" faces in clouds or the outlines of trees. The experiments of modern Gestalt psychology demonstrate a universal need to discover familiar patterns in apparently random groupings, a need that underlies the well-known "ink-blot" or Rohrschach tests. If we knew more about their historical origin, the constellations might provide useful information about the mental characteristics of the prehistoric societies that first traced them.

Learning the constellations is like gaining familiarity with a map and has the same purpose: the constellations make it easier to find one's way around the sky. Knowing the constellations, a man can readily find a comet reported to be "in Cygnus" (the Swan); he would almost certainly miss the comet if he knew only that it was "in the sky." The map provided by the constellations is, however, an unusual one because the constellations are always in motion. Since they all move together, preserving their patterns and their relative positions,

the motion does not destroy their usefulness. A star in Cygnus will always be in Cygnus, and Cygnus will always be the same distance from Ursa Major.* But neither Cygnus nor Ursa Major remains for long at the same position in the sky. They behave like cities on a map pasted to a rotating phonograph record.

Both the fixed relative positions and the motions of the stars are illustrated in Figure 5, which shows the location and orientation of the Big Dipper (part of Ursa Major) in the northern sky at three times during a single night. The pattern of seven stars in the Dipper is the same at each viewing. So is the relation of the Dipper to the North Star, which always lies 29° to the open side of the Dipper's bowl on a straight line through the last two stars in the bowl. Other diagrams would show similar permanent geometric relations among the other stars in the heavens.

Figure 5 displays another important characteristic of the stellar motions. As the constellations and the stars composing them swing through the skies together, the North Star remains very nearly stationary. Careful observation shows that it is not, in fact, quite stationary during any night, but there is another point in the heavens, now less than 1° away from the North Star, which has precisely the properties attributed to that star in Figure 5. This point is known as the north celestial pole. An observer at a given location in northern latitudes can always find it, hour after hour and night after night, at the same fixed distance above the due-north point on his horizon. A straight stick clamped so that it points toward the pole will continue to point toward the pole as the stars move. Simultaneously, however, the celestial pole behaves as a star. That is, the pole retains its geometric relations to the stars over long periods of time.† Since the pole is a fixed

* "Distance" here means "angular distance," that is, the number of degrees between two lines pointing from the observer's eye to the two celestial objects whose separation is to be measured. This is the only sort of distance that astronomers can measure directly, that is, without making calculations based upon some theory about the structure of the universe.

† Observations made many years apart show that the pole's position among the stars is very slowly changing (about 1° in 180 years). We shall neglect this slow motion, which is part of an effect known as the precession of the equinoxes, until Section 2 of the Technical Appendix. Though the ancients were aware of it by the end of the second century B.C., precession played a secondary role in the construction of their astronomical theories, and it does not alter the short-term observations described above. There has always been a north celestial pole at the same distance above the due-north point on the horizon, but the same stars have not always been near it.

point for each terrestrial observer and since the stars do not change their distance from this point as they move, every star seems to travel along the arc of a circle whose center is the celestial pole. Figure 5 shows a part of this circular motion for the stars in the Dipper.

The concentric circles traced by the circumpolar motions of the stars are known as their diurnal or daily circles, and the stars revolve in these circles at a rate just over 15° per hour. No star completes a full circle between sunset and sunrise, but a man observing the northern skies during a single clear night can follow stars near the pole through approximately a semicircle, and on the next night he can find them again moving along the same circles at the same rate. Furthermore, he will find them at just the positions they would have reached if they had continued their steady revolutions throughout the intervening day. Since antiquity, most observers equipped to recognize these regularities have naturally assumed that the stars exist and move during the day as during the night, but that during the day the strong light of the sun makes them invisible to the naked eye. On this interpretation the stars swing steadily through full circles, each star completing a circle once every 23 hours 56 minutes. A star that is directly below the pole at 9:00 o'clock on the evening of October 23 will return to the same position at 8:56 on the evening of October 24

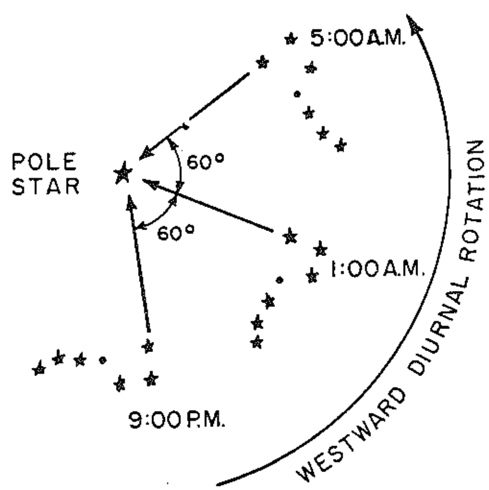


Figure 5. Successive positions of the Big Dipper at four-hour intervals on a night in late October.

and at 8:52 on October 25. By the end of the year it will be reaching its position below the pole before sunset and will therefore not be visible in that position at all.

In middle-northern latitudes the celestial pole is approximately 45° above the northernmost point on the horizon. (The elevation of the pole is precisely equal to the observer's angle of latitude – that is one way latitude is measured.) Therefore stars that lie within 45° of the pole, or whatever the elevation at the observer's location may be, can never fall below the horizon and must be visible at any hour of a clear night. These are the circumpolar stars, "those that know no destruction," in the words of the ancient Egyptian cosmologists. They are also the only stars whose motion is easily recognized as circular.

Stars farther from the poles also travel along diurnal circles, but part of each circle is hidden below the horizon (Figure 6). Therefore such stars can sometimes be seen rising or setting, appearing above or disappearing below the horizon; they are not always visible throughout the night. The farther from the pole such a star is, the less of its diurnal circle is above the horizon and the more difficult it is to recognize the visible portion of its path as part of a circle. For example, a star that rises due east is visible on only half of its diurnal circle. It travels very nearly the same path that the sun takes near one of the equinoxes, rising along a slant line up and to the south (Figure 7*a*), reaching its maximum height at a point over the right shoulder of an observer looking east, and finally setting due west along a line slanting downward and to the north. Stars still farther from the pole appear only briefly over the southern horizon. Near the due-south point they set very soon after they rise, and they never get very far above the horizon (Figure 7*b*). Since during almost half the year they rise and set during daylight, there are many nights when they do not appear at all.

These qualitative features of the night sky are common to the entire area within which ancient astronomical observations were made, but the description has glossed over significant quantitative differences. As an observer travels south, the elevation of the pole above the northern horizon decreases approximately 1° for every 69 miles of southward motion. The stars continue to move in diurnal circles about the pole, but since the pole is closer to the horizon, some stars that were circumpolar in the north are seen rising and setting by an observer farther south. Stars that rise and set due east and west continue to appear and disappear at the same points on the horizon, but toward the south they appear to move along a line more nearly perpendicular to the horizon, and they reach their maximum elevation more nearly

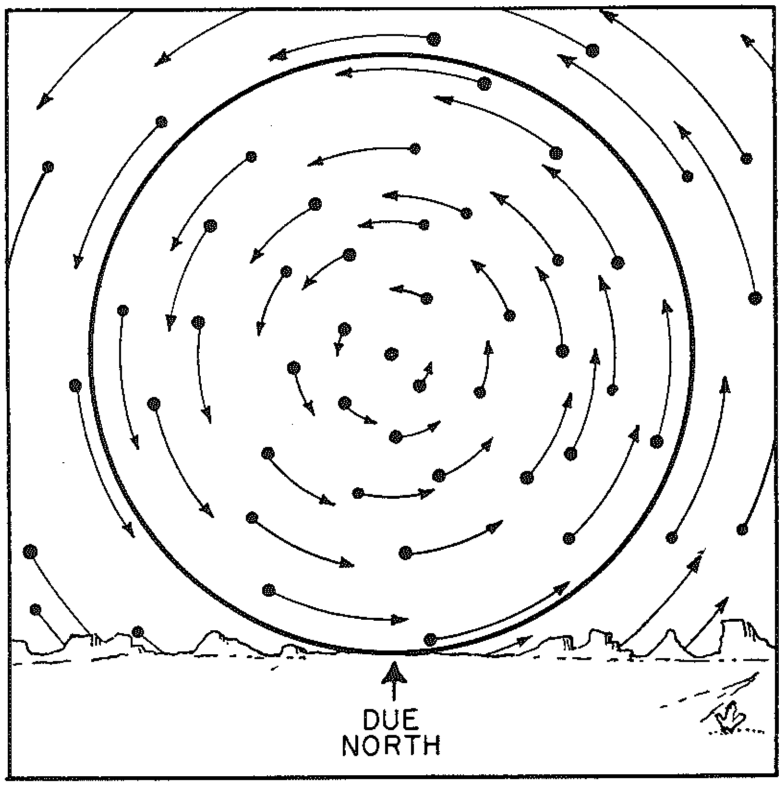


Figure 6. A set of the short circular arcs described by typical stars in the northern sky during a two-hour period. The heavy circle tangent to the horizon separates the circumpolar stars from those that rise and set.

Star trails like these can actually be recorded by pointing a fixed camera *at the celestial pole* and leaving the shutter open as the heavens turn. Each additional hour's exposure adds 15° to the length of every track. Notice, however, that the elevated camera angle introduces a deceptive distortion. If the pole is 45° above the horizon (a typical elevation in middle-northern latitudes), then a star that appears at the very top of the heavy circle is actually directly above the observer's head. Recognizing the distortion due to camera angle makes it possible to relate the star trails in this diagram to those shown more schematically in Figures 7*a* and *b*.

over the observer's head. The appearance of the southern sky changes more strikingly. As the pole declines toward the northern horizon, stars in the southern sky, because they remain at the same angular distance from the pole, rise to greater heights over the southern horizon. A star that barely rises above the horizon when seen from the north will rise higher and be seen for longer when observed from farther south. A southern observer will still see stars that barely peek above the southernmost point on his horizon, but these will be stars that the northern stargazer never sees at all. As an observer moves south, he sees fewer and fewer circumpolar stars – stars that are visible through-

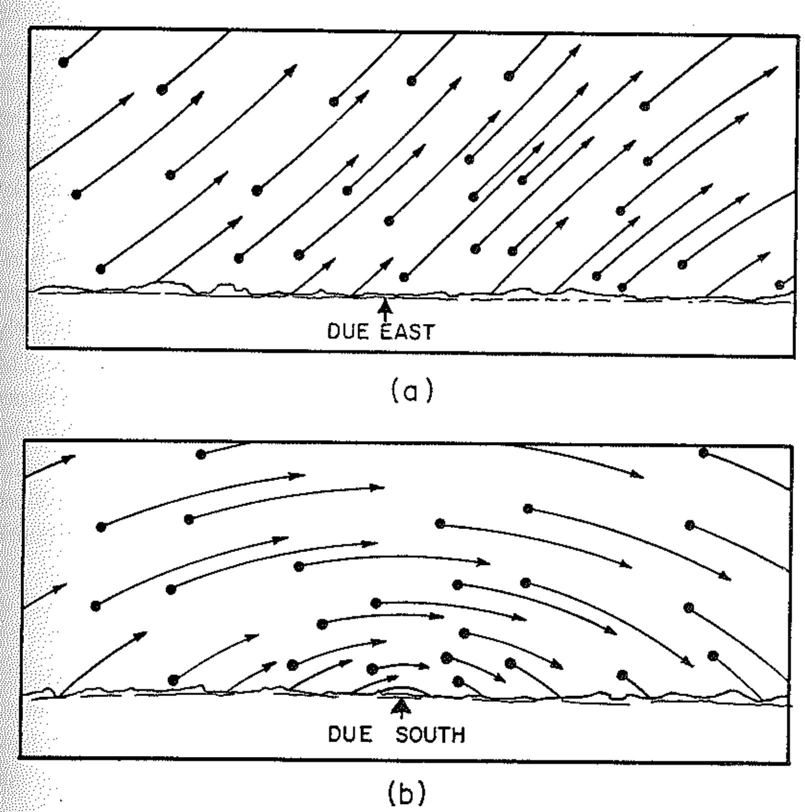


Figure 7. Star trails over (*a*) the eastern and (*b*) the southern horizon. Like Figure 6, these diagrams show the motion of typical stars over a 90° section of the horizon during a two-hour period. In these diagrams, however, the "camera" is directed to the horizon, so that only the first 40° above the horizon is shown.

out the night. But in the south he will, at some time or other, observe stars that an observer in the north can never see.

The Sun as a Moving Star

Because the stars and the celestial pole retain the same relative positions hour after hour and night after night, they can be permanently located upon a map of the heavens, a star map. One form of star map is shown in Figure 8; others will be found in any atlas or book on astronomy. The map of Figure 8 contains all the brighter stars that can ever be seen by an observer in middle-northern latitudes, but not all the stars on the map can be seen at once because they are not all above the horizon simultaneously. At any instant of the night approximately two-fifths of the stars on the map lie below the horizon.

The particular stars that are visible and the portion of sky in which they appear depend upon the date and hour of the observation. For example, the solid black line on the map broken by the four cardinal points of the compass, N, E, S, W, encloses the portion of the sky that is visible to an observer in middle-northern latitudes at 9:00 o'clock on the evening of October 23. It therefore represents his horizon. If the observer holds the map over his head with the bottom toward the north, the four compass points will be approximately aligned with the corresponding points on his physical horizon. The map then indicates that at this time of night and year the Big Dipper appears just over the northern horizon and that, for example, the constellation Cassiopeia lies at a position near the center of the horizon-window, corresponding to a position nearly overhead in the sky. Since the stars return to their positions in just 4 minutes less than 24 hours, the same orientation of the map must indicate the position of the stars at 8:56 on the evening of October 24, at 8:52 on October 25, at 8:32 on October 30, and so on.

Now imagine that the solid black horizon line which encloses the observer's field of view is held in its present position on the page while the entire disk of the map is rotated slowly behind it in a counterclockwise direction about the central pole. Rotating the disk 15° brings into the horizon-window just those stars that are visible at 10:00 o'clock on the evening of October 23, or at 9:56 on the evening of October 24, and so on. A rotation of 45° moves the stars visible at midnight on October 23 inside of the horizon line. The positions of all bright

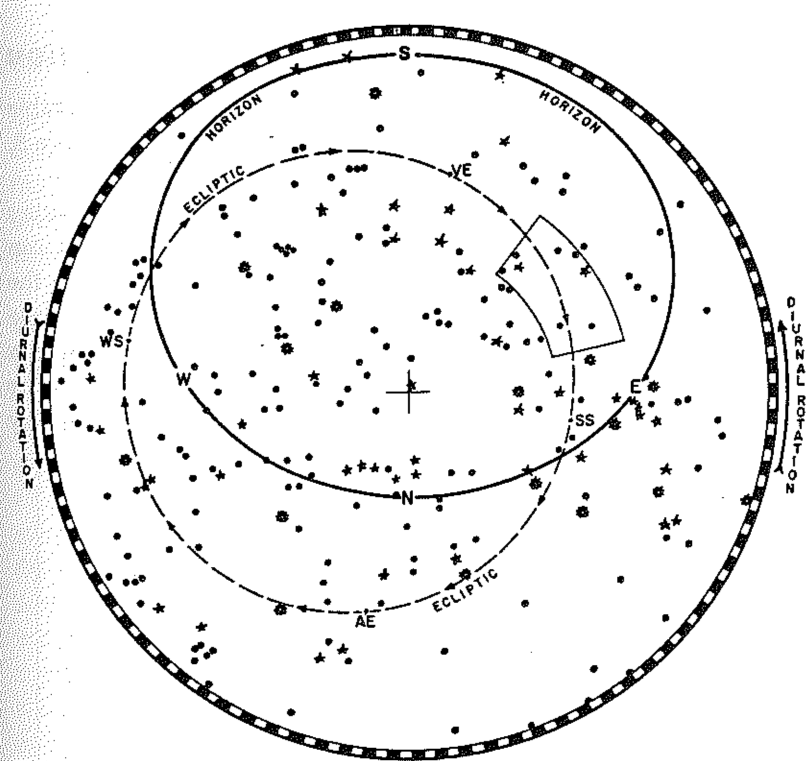


Figure 8. A circumpolar star map containing all the major stars ever visible to an observer at approximately 45° northern latitude. The cross at the geometric center of the map indicates the position of the celestial pole.

If the map is held horizontally overhead with its face toward the ground and with the bottom of the page pointing north, it will show the orientation of the stars as they appear to an observer in middle-northern latitudes at 9:00 o'clock on the evening of October 23. The stars within the solid line bounding the horizon-window are the ones that the observer can see; those outside the line are below the horizon on this day at this hour. Stars that lie within the horizon-window near the point *N* on the map will be seen just over the due-north point on the physical horizon (notice the Dipper); those near the east point, *E*, will be just rising in the east; and so on. To find the position of stars at a later hour on October 23, the horizon-window should be imagined stationary and the circular map should be rotated behind it, counterclockwise about the pole, 15° for each hour after 9:00 P.M. This motion leaves the pole stationary but carries stars up over the eastern horizon and down behind the western one. To find the positions of stars at 9:00 P.M. on a later day the map should be rotated clockwise behind the stationary horizon-window, 1° for each day after October 23. Combining these two procedures makes it possible to find the positions of stars at any hour of any night of the year.

The broken line that encircles the pole in the diagram is the ecliptic, the sun's apparent path through the stars (see p. 23). The box that encloses a portion of the ecliptic in the upper right-hand quadrant of the map contains the region of the sky shown in expanded form in Figures 9 and 15.

stars at any hour of any night can be found in this way. A movable star map equipped with a fixed horizon-window, like that in Figure 8, is frequently known as a "star finder."

Star maps have other applications, however, besides locating bodies that, like the stars, remain in constant relative positions. They can also be used to describe the behavior of celestial bodies that, like the moon, comets, or planets, slowly change their positions among the stars. For example, as the ancients knew, the sun's motion takes a particularly simple form as soon as it is related to the stars. Since the stars appear shortly after sunset, an observer who knows how to follow

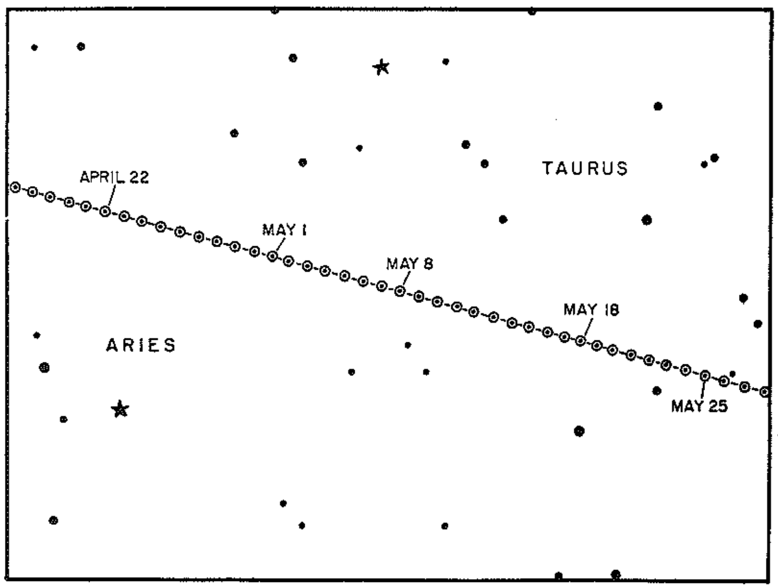


Figure 9. Motion of the sun through the constellations Aries and Taurus. The circles represent the sun's position among the stars at sunset on successive evenings from the middle of April to late May.

their motion can record the time and horizon position of the sunset, measure the time between sunset and the first appearance of the stars, and then locate the sun on a star map by rotating the map backward to determine which stars were at the appropriate horizon position when the sun set. An observer who plots the position of the sun on a star map for several consecutive evenings will find it in almost the same position each time. Figure 9 shows the position of the sun on a star

map on successive evenings for one month. It is not in the same position on the map for two successive observations, but it has not moved far. Each evening finds it about 1° from its position the previous evening, and 1° is a relatively small distance, about twice the angular diameter of the sun.

These observations suggest that both the daily motion of the sun and its slower shift north and south along the horizon may conveniently be analyzed by regarding the sun as a body that moves slowly among the stars from day to day. If, for some particular day, the position of the sun among the stars is specified, then, on that day, the sun's motion will be almost exactly the diurnal motion of a star in the corresponding position on the map. Both will move like points on the rotating map, rising in the east along a line slanting upward and to the south and later setting in the west. One month later the sun will again have the diurnal motion of a star, but now it will move very nearly like a star 30° away from the position of the star whose motion it copied a month earlier. During the intervening month the sun has moved slowly and steadily between these two positions, 30° apart on the map. Each day its motion has been almost that of a star, part of a circle about the pole of the heavens, but it has not behaved like quite the same star on two successive days.

If the sun's position is plotted on a star map day after day and the points marking its successive positions in the evening are connected together, a smooth curve is produced which rejoins itself at the end of a year. This is the curve, called the ecliptic, that is indicated by the broken line on the star map of Figure 8. The sun is always to be found somewhere on this line. As the ecliptic is carried rapidly through the heavens by the common diurnal motion of the stars, the sun is carried along with it, rising and setting like a star located at a point somewhere on the line. But simultaneously the sun is moving slowly around the ecliptic, occupying a slightly different position each day, hour, or minute. Thus the complex helical motion of the sun can be analyzed as the result of two much simpler motions. The total apparent motion of the sun is composed of its diurnal motion (the westward circle due to the counterclockwise motion of the whole map) and a simultaneous slow eastward motion (clockwise about the pole on the map) along the ecliptic.

Analyzed in this way, the sun's motion shows close parallels to the motion of a toll collector on a merry-go-round. The collector is carried around rapidly by the revolutions of the platform. But as he walks slowly from horse to horse collecting tolls his motion is not quite the same as that of the riders. If he walks in a direction opposite to that of the platform's spin, his motion over the ground will be slightly slower than that of the platform, and the riders will complete one circle somewhat more rapidly than he. If his toll collections carry him toward and away from the center of the platform, his total motion with respect to the ground will not be circular at all, but a complex curve which does not rejoin itself at the end of a single revolution. Though it is theoretically possible to specify precisely the path along which the toll collector moves over the stationary ground, it is far simpler to divide his total motion into its two component parts: a steady rapid rotation with the platform and a slower less regular motion with respect to the platform. Since antiquity astronomers have used a similar division in analyzing the apparent motion of the sun. Each day the sun moves rapidly westward *with the stars* (its so-called diurnal motion); simultaneously the sun moves slowly eastward along the ecliptic *through the stars* or *with respect to the stars* (its annual motion).

With the sun's total motion divided into two components, its behavior can be described simply and precisely merely by labeling neighboring points on the ecliptic with the day and hour at which the sun reaches each of them. The series of labeled points specifies the annual component of the sun's motion; the remaining diurnal component is specified by the daily rotation of the map as a whole. For example, since the ecliptic appears in Figure 8 as a somewhat distorted and considerably off-center circle, there must be one point, *SS*, on the ecliptic that is nearer the central pole than any other. No other point on the ecliptic rises and sets as far to the north as *SS*, and no other joint stays within the horizon-window for as long during the map's rotation. Therefore *SS* is the summer solstice, and the sun's center must pass through it around June 22. Similarly the points *AE* and *VE* in Figure 8 are the equinoctial points, the two points on the ecliptic that rise and set due east and west and that remain inside the horizon-window for exactly one-half of each map rotation. The center of the sun must pass through them on September 23 and March 21 respectively, just as it must pass through *WS*, the point on

the ecliptic farthest from the pole, on or near December 22. The solstices and equinoxes, which first appeared as days of the year, have now received a more precise and astronomically more useful definition. They are points on a star map or in the sky. Together with the corresponding dates (or instants, since the sun's center passes instantaneously through each point), these labeled positions on the ecliptic specify the direction and approximate rate of the sun's annual motion. Given these labels and others like them, a man who knows how to simulate the diurnal motion by rotating a star map can determine the hours and positions of sunrise and sunset and the maximum height of the sun on every day of the year.

The solstices and the equinoxes are not the only positions on the ecliptic to receive standard labels. Drawn on a star map, the ecliptic passes through a group of particularly prominent constellations, known as the signs of the zodiac. By a convention dating from remote antiquity these signs divide the ecliptic into twelve segments of equal length. To say that the sun is "in" a particular constellation is to specify approximately its position on the ecliptic, which, in turn, specifies the season of the year. The annual journey of the sun through the twelve signs seems to control the cycle of the seasons, an observation that is one root of the science or pseudo science of astrology with which we shall deal further in Chaper 3.

The Birth of Scientific Cosmology — The Two-Sphere Universe

The observations described in the last three sections are an important part of the data used by ancient astronomers in analyzing the structure of the universe. Yet, in themselves, these observations provide no direct structural information. They tell nothing about the composition of the heavenly bodies or their distance; they give no explicit information about the size, position, or shape of the earth. Though the method of reporting the observations has disguised the fact, they do not even indicate that the celestial bodies really move. An observer can only be sure that the angular distance between a celestial body and the horizon changes continually. The change might as easily be caused by a motion of the horizon as by a motion of the heavenly body. Terms like sunset, sunrise, and diurnal motion of a star do not, strictly speaking, belong in a record of observation at all. They are parts of an interpretation of the data, and though this interpretation is so natural that it can scarcely be kept out of the vocabulary with which the observations are discussed, it does go beyond the content of the observations themselves. Two astronomers can agree perfectly about the results of observation and yet disagree sharply about questions like the reality of the motion of the stars.

Observations like those discussed above are therefore only clues to a puzzle for which the theories invented by astronomers are tentative solutions. The clues are in some sense objective, given by nature; the numerical result of this sort of observation depends very little upon the imagination or personality of the observer (though the way in which the data are arranged may). But the theories or conceptual schemes derived from these observations do depend upon the imagination of scientists. They are subjective through and through. Therefore, observations like those discussed in the preceding sections could be collected and put in systematic form by men whose beliefs about the structure of the universe resembled those of the ancient Egyptians. The observations in themselves have no *direct* cosmological consequences; they need not be, and for many millennia were not, taken very seriously in the construction of cosmologies. The tradition that detailed astronomical observations supply the principal clues for cosmological thought is, in its essentials, native to Western civilization. It seems to be one of the most significant and characteristic novelties that we inherit from the civilization of ancient Greece.

A concern to explain observations of the stars and planets is apparent in our oldest fragmentary records of Greek cosmological thought. Early in the sixth century B.C., Anaximander of Miletus taught:

> The stars are compressed portions of air, in the shape of [rotating] wheels filled with fire, and they emit flames at some point from small openings. . . .
>
> The sun is a circle twenty-eight times the size of the earth; it is like a chariot-wheel, the rim of which is hollow and full of fire, and lets the fire shine out at a certain point in it through an opening like the nozzle of a pair of bellows. . . .
>
> The eclipses of the sun occur through the orifice by which the fire finds vent being shut up.
>
> The moon is a circle nineteen times as large as the earth; it is like a chariot-wheel, the rim of which is hollow and full of fire, like the circle of the sun, and it is placed obliquely, as that of the sun also is; it has one vent like the nozzle of a pair of bellows; its eclipses depend on the turnings of the wheel.[1]

Astronomically these conceptions are far in advance of the Egyptians'. The gods have vanished in favor of mechanisms familiar on the earth. The size and position of the stars and planets are discussed. Though the answers given seem extremely rudimentary, the problems had to be raised before they could receive mature and considered solutions. In the fragment quoted the diurnal circles of the stars and the sun are handled with some success by treating the celestial bodies as orifices on the rims of rotating wheels. The mechanisms for eclipses and for the annual wandering of the sun (the latter accounted for by the oblique position of the sun's circle) are less successful, but they are at least begun. Astronomy has started to play a major role in cosmological thought.

Not all the Greek philosophers and astronomers agreed with Anaximander. Some of his contemporaries and successors advanced other theories, but they advanced them for the same problems and they employed the same techniques in arriving at solutions. For us it is the problems and techniques that are important. The competing theories need not be traced; moreover, they cannot be traced completely, for the historical records are too incomplete to permit more than conjecture about the evolution of the earliest Greek conceptions of the universe. Only in the fourth century B.C. do the records become approximately reliable, and by that time, as the result of a long evolutionary process, a large measure of agreement about cosmological essentials had been reached. For most Greek astronomers and philosophers, from the fourth century on, the earth was a tiny sphere suspended stationary at the geometric center of a much larger rotating sphere which carried the stars. The sun moved in the vast space between the earth and the sphere of the stars. Outside of the outer sphere there was nothing at all – no space, no matter, nothing. This was not, in antiquity, the only theory of the universe, but it is the one that gained most adherents, and it is a developed version of this theory that the medieval and modern world inherited from the ancients.

This is what I shall henceforth call the "two-sphere universe," consisting of an interior sphere for man and an exterior sphere for the stars. The phrase is, of course, an anachronism. As we shall see in the next chapter, all those philosophers and astronomers who believed in the terrestrial and celestial spheres also postulated some additional cosmological device to carry the sun, moon, and planets around in the space that lay between them. Therefore the two-sphere universe is not really a cosmology at all, but only the structural framework for one. Furthermore, that structural framework housed a great many different and controversial astronomical and cosmological schemes during the nineteen hundred years that separate the fourth century B.C. from the age of Copernicus. There were many two-sphere universes. But, after its first establishment, the two-sphere framework itself was almost never questioned. For very nearly two millennia it guided the imagination of all astronomers and most philosophers. That is why we begin our discussion of the main Western astronomical tradition by considering the two-sphere universe, framework though it is, in abstraction from the various planetary devices advanced by one astronomer or another to complete it.

The origin of the two-sphere framework is obscure, but the source of its persuasiveness is not. The sphere of the heavens is only a short step from the domed heaven of the Egyptians and Babylonians, and the heavens do look domed. The elongation that the Egyptians gave to the heavens vanishes in a society not based upon a river like the Nile and leaves a hemispherical shell. Connecting the vault above the earth with a symmetric vault below gives the universe an appropriate and satisfying closure. The rotation of the resulting sphere is indicated by the stars themselves; as we shall shortly see, a steady rotation of the outer sphere, once every 23 hours 56 minutes, will produce just the diurnal circles that we have already described.

There is, in addition, an essentially aesthetic argument in favor of the spherical universe. Since the stars seem as far away as anything we can see and since they all move together, it is natural to suppose that they are simply markings on the outer surface of the universe and that they move with it. Furthermore, since the stars move eternally with perfect regularity, the surface on which they move ought itself be perfectly regular and it should move in the same manner forever. What figure better fulfills these conditions than the sphere, the only completely symmetric surface and one of the few that can turn eternally upon itself, occupying exactly the same space in each instant of its motion? In what other form could an eternal and self-sufficient universe be created? This is essentially the argument employed by the Greek philosopher Plato (fourth century B.C.) in his *Timaeus*, an allegorical story of the creation in which the universe appears as an organism, an animal.

> [The Creator's] intention was, in the first place, that the animal should be as far as possible a perfect whole and of perfect parts: secondly, that it should be one, leaving no remnants out of which another such world might be created: and also that it should be free from old age [eternal] and unaffected by disease [incorruptible] . . . . Wherefore he made the world in the form of a globe, round as from a lathe, having its extremes in every direction equidistant from the center, the most perfect and the most like itself of all figures; for he considered that the like is infinitely fairer than the unlike. This he finished off, making the surface smooth all round for many reasons; in the first place, because the living being had no need of eyes when there was nothing remaining outside him to be seen; nor of ears when there was nothing to be heard; and there was no surrounding atmosphere to be breathed; nor would there have been any use of organs by the help of which he might receive his food or get rid of what he had already digested, since there was nothing which went from him or came into him: for there was nothing beside him. Of design he was created thus, his own waste providing his own food, and all that he did or suffered taking place in and by himself. For the Creator conceived that a being which was self-sufficient would be far more excellent than one which lacked anything; and, as he had no need to take anything or defend himself against any one, the Creator did not think it necessary to bestow upon him hands: nor had he any need of feet, nor of the whole apparatus of walking; but the movement suited to his spherical form was assigned to him, . . . and he was made to move in the same manner and on the same spot, within his own limits revolving in a circle.[2]

Some of the ancient arguments for the sphericity of the earth are of the same sort: what is more fitting than that the earth, man's abode, should display the same perfect figure with which the universe was created? But many of the demonstrations are more concrete and familiar. The hull of a ship sailing from shore disappears before the top of the mast. More of the ship and of the sea is visible from a high observation point than from a low one (Figure 10). The shadow of the earth on the moon during a lunar eclipse always has a circular edge. (This explanation of eclipses, current even before the fourth century B.C., is discussed in Section 3 of the Technical Appendix.) These arguments are still difficult to evade or refute, and in antiquity their effectiveness extended by analogy from the earth to the heavens: a celestial region that mirrored the shape of the earth seemed specially appropriate. Other arguments derived from the similarity and symmetric arrangement of the two spheres. The earth's central position, for example, kept it stationary in the spherical universe. In which direction can a body fall from the center of a sphere? There is no "down" at the

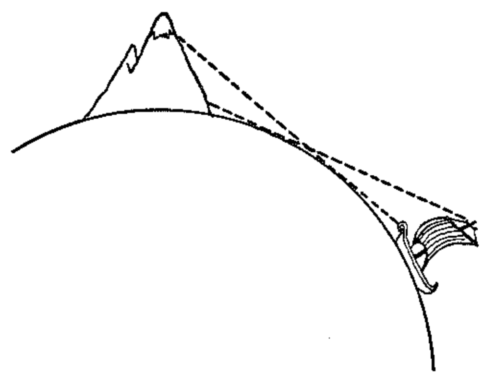


Figure 10. An ancient (and modern) argument for the earth's sphericity. An observer at the base of the mountain can see only the tip of the ship's mast over the earth's bulge. From the mountain top the entire mast and part of the hull are visible.

center, and every direction is equally "up." Therefore the earth must hang at the center, eternally stable as the universe rotates about it.

Though these arguments from symmetry may seem strange today (arguments for a discredited conclusion usually do seem strange), they were very important in ancient, medieval, and early modern thought. A discussion of symmetry, like Plato's, displays the appropriateness of the two-sphere cosmology; it explains why the universe was created in the spherical form. Even more important, as we shall discover in Chapters 3 and 4, the symmetry of the two spheres provided important links between astronomical, physical, and theological thought, because it was essential to each. In Chapter 5 we shall find Copernicus struggling vainly to preserve the essential symmetry of ancient cosmology in a universe constructed to contain a moving planetary earth. But we are now most concerned with the astronomical functions of the two-sphere universe, and here the case is entirely clear. In astronomy the two-sphere cosmology works and works very well. That is, it accounts precisely for the observations of the heavens described in the earlier portions of this chapter.

Figure 11 shows a spherical earth, much exaggerated in size, at the center of a larger sphere of the stars. An observer on the earth, at a position indicated by the arrow, O, can see just half of the sphere. His horizon is bounded by a plane (shaded in the diagram) tangent to the earth at the point where he is standing. If the earth is very small

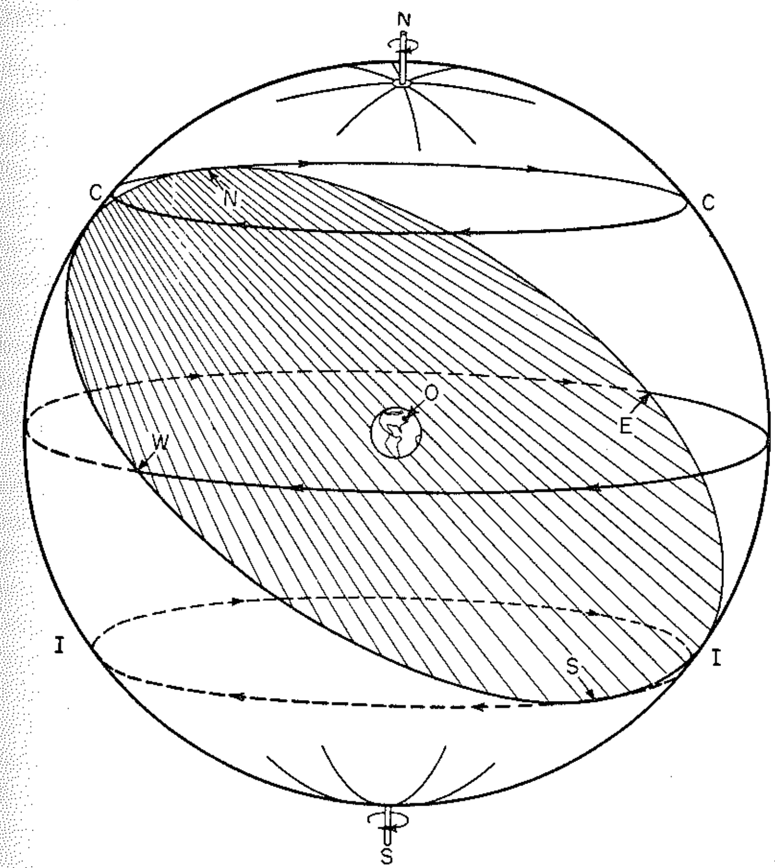


Figure 11. Astronomical functions of the two-sphere universe. The outermost circle is a cross section of the sphere of the stars which rotates steadily eastward about the axis *NS*. The observer at *O* can see all portions of this sphere that lie above the shaded horizon plane *SWNE*. If the diagram were drawn to scale, the earth would be much reduced and the horizon plane would be tangent to the earth at the observation point. But since a scale drawing would reduce the earth to minuscule dimensions, the plane is here drawn through the center of the sphere of the stars, and its orientation with respect to the observer is preserved by keeping it perpendicular to the line from the observer to the earth's center.

The horizontal circles in the diagram are the paths traced by selected points on the sphere as the sphere goes through its daily rotation. They are therefore the diurnal circles of selected stars, drawn solid where they are visible to the observer and broken where they lie below the horizon. The central circle is traced by a star on the celestial equator. It rises at *E*, due east of the observer, moves upward along a line slanting south, and so on. The uppermost and lowermost circles are traced by stars that meet the horizon in only one point. The upper circle, *CC*, is the diurnal circle of the southernmost circumpolar star; the lower circle, *II*, is traced by the northernmost of the stars that remain invisible to the observer at *O*.

compared with the sphere of the stars, this tangent plane will divide the outer sphere into two almost precisely equal parts, one visible to the observer, and the other hidden from him by the surface of the earth. Any objects permanently mounted on the outer sphere will, like the stars, retain the same relative positions when seen from the tiny central earth. If the sphere turns steadily about an axis through the diametrically opposite points *N* and *S*, all the stars will move with it unless they are actually located at *N* or *S*. Since *S* is invisible to the observer in the diagram, *N* is the single stationary point in his heaven, his celestial pole, and it is in fact located just about 45° over the due-north point on his horizon, as it should be for an observer at *O*, a point in middle-northern latitudes.

Objects near the point *N* on the outer sphere appear to the observer at *O* to rotate slowly in circles about the pole; if the sphere rotates once in every 23 hours 56 minutes, these objects complete their circles in the same period as the stars; they represent stars in the model. All stars that lie near enough the pole to be inside the circle *CC* on the diagram are circumpolar, for the sphere's rotation never carries them below the horizon. Stars that lie farther from *N*, between the circles *CC* and *II*, rise and set at an angle to the horizon once in each rotation of the sphere, but stars nearest the circle *II* barely get above the southern horizon and are visible only briefly. Finally, stars located within the circle *II*, near *S*, never appear to the observer at *O*; they are always hidden by his horizon. They would, however, be visible to an observer at other locations on the inner sphere; *S* is at least a potentially visible fixed point in the heavens, a second pole. Call it the south celestial pole and the visible point at *N* the north celestial pole.

If the observer in the diagram moves northward from *O* (that is, toward a point on the inner sphere directly under the north celestial pole), his horizon plane must move with him, becoming more and more nearly perpendicular to the axis of the stellar sphere as he approaches the terrestrial pole. Therefore, as the observer moves north, the celestial pole must appear farther and farther from the north point on the horizon until at last it lies directly over his head. Simultaneously, the circle *CC*, always drawn tangent to the northernmost point on the horizon, must expand so that more and more stars become circumpolar. Since the circle *II* also expands when the observer moves north, the number of invisible stars must increase as well. If the observer moves

south, the effects are exactly reversed, the pole coming closer and closer to the north point on the horizon and the circles *CC* and *II* shrinking in size until they just enclose the north and south celestial poles when the observer gets to the equator. Figure 12 shows the two limiting cases, an observer at the north pole of the earth and an observer at the terrestrial equator. In the first case the horizon is shown horizontal; the north celestial pole is directly over the observer's head;

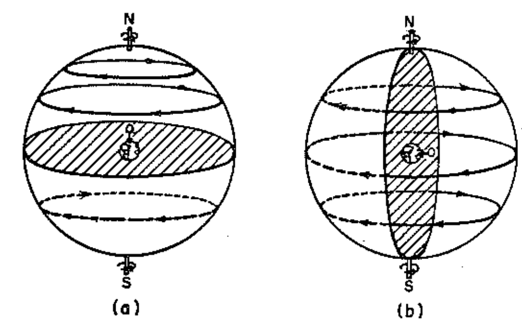


Figure 12. Stellar motions in the two-sphere universe as seen by an observer (*a*) at the north terrestrial pole and (*b*) at the equator.

the stars in the upper half of the sphere swing continuously in circles parallel to the horizon; and the stars in the lower hemisphere are never seen at all. In the second diagram the horizon is vertical; the north and south celestial poles are fixed at the north and south points on the horizon; all stars can be seen at some time or other; but none can be seen through more than a semicircle.

Except that these last extreme examples were not observed in antiquity, the motion of the stars in the two-sphere model of the universe coincides precisely with the previously discussed observations of real stars. There is no more convincing argument for the two-sphere cosmology.

The Sun in the Two-Sphere Universe

A complete discussion of the sun's motion in the two-sphere universe demands that the cosmology be elaborated to account for the sun's intermediate position between the central earth and the peripheral rotating stellar sphere. This elaboration is part of the larger problem of the planets; it will be considered in the next chapter. But even the skeletal cosmology described above permits a great simplification in the description of the sun's apparent motion. Seen from the central earth against the spherical backdrop provided by the stellar sphere, the sun's motion acquires a regularity that was not apparent until the stars were localized on a rotating earth-centered sphere.

The new simplicity of the sun's apparent motion is described in Figure 13, which is a reduced sketch of the stellar sphere with its north pole visible and with the direction of westward diurnal rotation indicated by an arrow about the pole. Halfway between the north and south celestial poles is drawn the celestial equator, a great circle on which lie all the stars (and all points on the sphere) that rise and set exactly due east and west. A great circle is the simplest of all curves that can be drawn on the surface of a sphere – the intersection of the sphere's surface with that of a plane through the sphere's center – and the new simplicity of the sun's motion results from the fact that on a celestial sphere the ecliptic, too, is just a great circle, dividing the sphere into two equal halves. In Figure 13 the ecliptic is the slanted

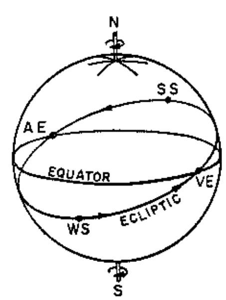


Figure 13. The equator and the ecliptic on the celestial sphere.

circle, intersecting the celestial equator in two diametrically opposite points at an angle of 23½°; it contains all the points at which the center of the sun is seen against the sphere of the stars by an observer on the earth. At each instant the sun's center appears at a point on this great circle, participating in the diurnal westward motion of the whole sphere, but simultaneously the sun slips slowly eastward (arrows in diagram), completing its journey around the ecliptic once in a year.

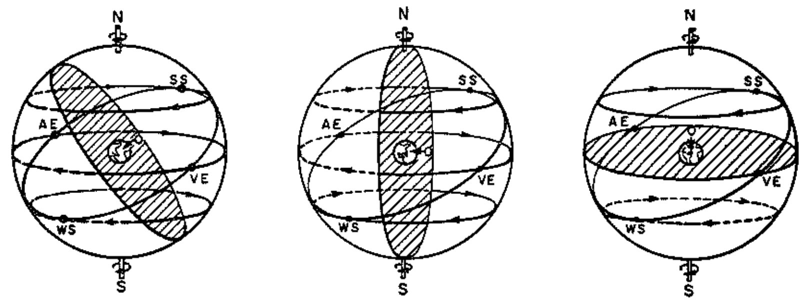
Because, during any 24-hour period, the sun appears to remain very near a single point on the ecliptic, it must move daily in a diurnal circle

very much like that of a star. But the sun moves slowly eastward with respect to the sphere as the sphere itself turns rapidly westward. Therefore the sun must complete its diurnal circle slightly more slowly than the stars complete theirs, losing a little ground in its race with the stars each day and being completely "lapped" by them once each year. More precisely, since the sun must move through 360° to traverse the ecliptic and since it completes this journey in just over 365 days, its eastward motion along the ecliptic must cover just under 1° per day, and this is the figure derived earlier from observation (p. 23). It is the distance which the sun slips backward (or loses) with respect to the stars each day. Furthermore, since the length of the day is defined by the diurnal motion of the sun and since the stars (moving 15° per hour or 1° every 4 minutes) get 1° farther ahead of the sun each day, a star that gets, say, overhead at midnight tonight will complete its diurnal motion and return to the same position in the sky just 4 minutes before midnight tomorrow night. Once again a detail about the behavior of the heavens, initially introduced as one among many assorted observations (p. 16), has become part of a coherent pattern in the two-sphere universe.

A similar order is apparent in the positions that the equinoxes and solstices assume on the stellar sphere. The two equinoxes must be the two diametrically opposite positions on the stellar sphere where the ecliptic intersects the celestial equator. These are the only points on the ecliptic that always rise and set due east and west. Similarly, the two solstices must be the points on the ecliptic midway between the two equinoxes, for these are the points on the ecliptic that lie farthest north and south of the celestial equator. When the sun is at one of these points it must rise farther north (or south) of the due-east point than it does at any other time. Since the sun moves steadily eastward from the summer solstice toward the autumnal equinox, the individual equinoxes and solstices are readily identified on the sphere. Each of them is labeled on the ecliptic in Figure 13, and once the ecliptic has been drawn and labeled in this manner it is possible, by constructing an appropriate horizon plane inside the stellar sphere, to discover how the sun's behavior varies during the course of a year when observed from any location on the earth's surface. Three particularly significant examples of the sun's motion at various seasons of the year are derived from the two-sphere conceptual scheme in the diagrams of Figure 14. In these diagrams the full force of the conceptual scheme begins to appear.

The Functions of a Conceptual Scheme

Unlike the observations described in the early sections of this chapter, the two-sphere universe is a product of the human imagination. It is a conceptual scheme, a theory, deriving from observations but simultaneously transcending them. Because it will not yet account



(a) (b) (c)

Figure 14. The motion of the sun observed from different locations on the earth.

(*a*) Observer in middle-northern latitudes: At the summer solstice the sun rises along a slanting line far north of the due-east point; more than one-half of its diurnal circle lies above the horizon, so that the days are longer than the nights. At the equinoxes the sun rises due east, and only one-half of its diurnal circle is visible. At the winter solstice the sun rises far to the south, and the days are shorter than the nights. The sun's maximum daily elevation above the horizon is greatest in summer, but at all seasons the sun's noon shadow must point due north.

(*b*) Observer at the equator: Whatever the sun's location on the ecliptic, the horizon plane divides the sun's diurnal circle into two equal parts. Days and nights are always of equal length, and there is little seasonal variation of climate. During half the year (vernal equinox to autumnal equinox) the sun rises north of the due-east point, and its noon shadow points due south. During the other half year the sun rises south of east, and its noon shadow points north.

(*c*) Observer at the north terrestrial pole: Half of the ecliptic is always below the horizon, so that for half the year (autumnal to vernal equinox) the sun is completely invisible. At the vernal equinox the sun begins to peek above the horizon, swinging around it daily in a gradually rising spiral until the summer solstice. Then the sun gradually spirals back to the horizon, disappearing slowly below it at the autumnal equinox. Between the vernal and autumnal equinoxes the sun does not set.

for the motions of all celestial bodies (the planets, in particular, have been ignored to this point), the two-sphere cosmology is not complete. But already it provides cogent illustrations of some logical and psychological functions that scientific theories can perform for the men who develop or make use of them. The evolution of any scientific conceptual scheme, astronomical or nonastronomical, depends upon the way in which it performs these functions. By making some of them explicit before the two-sphere universe is elaborated in the next two chapters, we can highlight in advance a few of the most fundamental problems that will emerge during this study of the Copernican Revolution.

Perhaps the most striking characteristic of the two-sphere universe is the assistance that it gives to the astronomer's memory. This characteristic of a conceptual scheme is often called conceptual economy. Though they were both carefully selected and systematically presented, the observations of the sun and stars discussed in earlier sections were, as a group, extremely complex. To a man not already thoroughly acquainted with the heavens, one observation, like the direction of the slant line along which the sun rises or the corresponding behavior of the gnomon's shadow, seems unrelated to another observation, like the location of the celestial pole or the brief appearance of the stars in the southern sky. Each observation is a separate item in a long list of bare facts about the heavens, and it is difficult to retain the whole list in memory simultaneously.

The two-sphere universe presents no such problem: a gigantic sphere bearing the stars rotates steadily westward on a fixed axis once every 23 hours 56 minutes; the ecliptic is a great circle on this sphere tilted 23½° to the celestial equator, and the sun moves steadily eastward about the ecliptic once every 365¼ days; the sun and stars are observed from a tiny fixed sphere located at the center of the giant stellar sphere. That much can be committed to memory once and for all, and while it is remembered the list of observations may be forgotten. The model replaces the list, because, as we have already seen, the observations can be derived from the model. Frequently they need not even be derived. A man who observes the heavens with the two-sphere universe firmly fixed in his mind will find that the conceptual scheme discloses a pattern among otherwise unrelated observations, that a list of the observations becomes a coherent whole for the first time, and that the individual items on the list are therefore more easily remembered. Without these ordered summaries which its theories provide science would be unable to accumulate such immense stores of detailed information about nature.

Because it provides a compact summary of a vast quantity of important observational materials, the two-sphere universe is actively employed by many people today. The theory and practice of both navigation and surveying can be developed with great simplicity and precision from models built to the specifications of Figure 11, and, since the model demanded by modern astronomy is far more complex, the two-sphere universe is normally used in preference to the Copernican when teaching these subjects. Most handbooks of navigation or surveying open with some sentence like this: "For present purposes we shall assume that the earth is a small stationary sphere whose center coincides with that of a much larger rotating stellar sphere." Evaluated in terms of economy, the two-sphere universe therefore remains what it has always been: an extremely successful theory.

In other respects, however, the two-sphere universe is no longer at all successful and has not been since the Copernican Revolution. It has remained economical only because economy is a purely logical function. The celestial observations known to ancient astronomers and used by modern navigators are logical consequences of the two-sphere model whether or not the model is thought to represent reality. The attitude of the scientist, his belief in the "truth" of the conceptual scheme, does not affect the scheme's logical ability to provide an economical summary. But conceptual schemes have psychological as well as logical functions, and these do depend upon the scientist's belief or incredulity. For example, the psychological craving for at-homeness, discussed in the second section, can be satisfied by a conceptual scheme only if that scheme is thought to be more than a convenient device for summarizing what is already known. During antiquity and again in the later Middle Ages the European world did have this additional commitment to the conception of a two-sphere universe. Scientists and nonscientists alike believed that the stars really were bright spots on a gigantic sphere that symmetrically enclosed man's terrestrial abode. As a result, two-sphere cosmology did for centuries provide many men with a world view, defining their place in the created world and giving physical meaning to their relation with the gods. As we shall see in

Chapters 3 and 4, a conceptual scheme that is believed and that therefore functions as part of a cosmology has more than scientific significance.

Belief also affects the way in which conceptual schemes function within the sciences. Economy as a purely logical function, and cosmological satisfaction as a purely psychological function, lie at opposite ends of a spectrum. Many other significant functions lie within the spectrum, between these limits, depending both upon the logical structure of the theory and upon its psychological appeal, its ability to evoke belief. For example, an astronomer who believes in the validity of the two-sphere universe will find that the theory not only provides a convenient summary of the appearances, but that it also *explains* them, enabling him to *understand* why they are what they are. Words like "explain" and "understand" apparently refer simultaneously to the logical and psychological aspects of conceptual schemes. Logically, the two-sphere universe explains the motions of the stars because the motions can be deduced from the far simpler model. Complexity is reduced, and such logical reduction is one essential component of explanation. But it is not the only one. Psychologically, the two-sphere universe provides no explanation unless it is believed to be true. The modern navigator uses the two-sphere universe on his job, but he does not explain the stellar motions in terms of a rotation of the outer sphere. He believes that the diurnal motion of the stars is only an apparent motion, and he must therefore explain it as the result of a real rotation of the earth.

A scientist's willingness to use a conceptual scheme in explanations is an index of his commitment to the scheme, a token of his belief that his model is the only valid one. Such commitment or belief is always rash, because economy and cosmological satisfaction cannot guarantee truth, whatever "truth" may mean. The history of science is cluttered with the relics of conceptual schemes that were once fervently believed and that have since been replaced by incompatible theories. There is no way of proving that a conceptual scheme is final. But, rash or not, this commitment to a conceptual scheme is a common phenomenon in the sciences, and it seems an indispensable one, because it endows conceptual schemes with one new and all-important function. Conceptual schemes are comprehensive; their consequences are not limited to what is already known. Therefore, an astronomer committed to, say, the two-sphere universe will expect nature to show the additional, but as yet unobserved, properties that the conceptual scheme predicts. For him the theory will transcend the known, becoming first and foremost a powerful tool for predicting and exploring the unknown. It will affect the future of science as well as its past.

The two-sphere universe tells the scientist about the behavior of the sun and stars in parts of the world (like the southern hemisphere and the terrestrial poles) to which he has never traveled. In addition it informs him of the motion of stars that he has never observed systematically. Since they are fastened to the stellar sphere, they must revolve in diurnal circles as the other stars do. This is new knowledge, derived initially not from observation but directly from the conceptual scheme, and such new knowledge can be immensely consequential. For example, two-sphere cosmology states that the earth has a circumference, and it suggests a set of observations (discussed in Section 4 of the Technical Appendix) by which the astronomer can discover how large the earth's circumference is. One set of these observations (a bad one, as it happened, for the resulting value of the circumference was far too small) led Columbus to believe that the circumnavigation of the globe was a practical undertaking, and the results of his voyages have been recorded. Those voyages and the subsequent travels of Magellan and others provided observational evidence for beliefs that had previously been derived solely from theory, and they supplied science with many unanticipated observations besides. The voyages would not have been undertaken, and the novel observations would not have accrued to the sciences, if a conceptual scheme had not pointed the way.

Columbus' voyages are one example of the fruitfulness of a conceptual scheme. They show how theories can guide a scientist into the unknown, telling him where to look and what he may expect to find, and this is perhaps the single most important function of conceptual schemes in science. But the guidance provided by conceptual schemes is rarely so direct and unequivocal as that illustrated above. Typically a conceptual scheme provides hints for the organization of research rather than explicit directives, and the pursuit of these hints usually requires extension or modification of the conceptual scheme that provided them. For example, the two-sphere universe was initially developed principally to account for the diurnal motions of the stars and for the way in which those motions varied with the observer's location on the earth. But once it had been developed, the new theory was readily extended to give order and simplicity to observations of the sun's motion as well. And, having disclosed the unsuspected regularity that underlay the complexity of the sun's behavior, the conceptual scheme provided a framework within which could be studied the even more irregular motions of the planets. That problem had seemed unmanageable until the over-all motion of the heavens was reduced to order.

Much of this book will be concerned with the fruitfulness of particular conceptual schemes, that is, with their effectiveness as guides for research and as frameworks for the organization of knowledge. The next two chapters, in particular, will examine the role of the two-sphere universe in the ancient solution, first, of the problem of the planets and, then, of some problems lying entirely outside astronomy. Later we shall discover the rather different sort of guidance given to scientific research by Copernicus' novel conception of a moving planetary earth. The very best example of fruitfulness is, however, the story told in the whole of this book. The Copernican universe is itself the product of a series of investigations that the two-sphere universe made possible: the conception of a planetary earth is the most forceful illustration of the effective guidance given to science by the incompatible conception of a unique central earth. That is why a discussion of the Copernican Revolution must begin with a study of the two-sphere cosmology which Copernicanism ultimately made obsolete. The two-sphere universe is the parent of the Copernican; no conceptual scheme is born from nothing.

Ancient Competitors of the Two-Sphere Universe

The two-sphere conception of the universe was not the only cosmology suggested in ancient Greece. But it was the one taken most seriously by the largest number of people, particularly by astronomers, and it was the one that later Western civilization first inherited from the Greeks. Yet many of the alternate cosmologies proposed and rejected in antiquity show far closer resemblances to modern cosmological beliefs than does the two-sphere universe. Nothing more clearly illustrates the strengths of the two-sphere cosmology and foreshadows the difficulties to be encountered in overthrowing it than a comparison of the scheme with a few of its superficially more modern alternatives.

As early as the fifth century B.C., the Greek atomists, Leucippus and Democritus, visualized the universe as an infinite empty space, populated by an infinite number of minute indivisible particles or atoms moving in all directions. In their universe the earth was but one of many essentially similar heavenly bodies formed by the chance aggregation of atoms. It was not unique, nor at rest, nor at the center. In fact, an infinite universe has no center; each part of space is like every other; therefore the infinite number of atoms, some of which aggregated to form our earth and sun, must have formed numerous other worlds in other portions of the empty space or void. For the atomists there were other suns and other earths among the stars.

Later in the fifth century the followers of Pythagoras suggested a second cosmology which set the earth in motion and partially deprived it of its unique status. The Pythagoreans did place the stars on a gigantic moving sphere, but at the center of this sphere they placed an immense fire, the Altar of Zeus, invisible from the earth. The fire could not be seen, because the earth's populated areas were always turned away from the fire. For the Pythagoreans the earth was just one of a number of celestial bodies, including the sun, all of which moved in circles about the central fire. A century later Heraclides of Pontus (fourth century B.C.) suggested that it was a daily rotation of the central earth rather than a rotation of the peripheral sphere of the stars that produced the apparent motion of the heavens. He also obscured the symmetry of the two-sphere universe by suggesting that the planets Mercury and Venus revolved in circles about the moving sun rather than in independent circular orbits about the central earth (see Chapter 2). Still later, in the middle of the third century B.C., Aristarchus of Samos, whose ingenious and influential measurements of astronomical dimensions are described in the Technical Appendix, advanced the proposal that has earned for him the title of "the Copernicus of antiquity." For Aristarchus the sun was at the center of an immensely expanded sphere of the stars, and the earth moved in a circle about the sun.

These alternative cosmologies, particularly the first and last, are remarkably like our modern views. We do believe today that the earth is but one of a number of planets, circulating about the sun, and that

the sun is but one of a multitude of stars, some of which may have their own planets. But though some of these speculative suggestions gave rise to significant minority traditions in antiquity, and though all of them were a continuing source of intellectual stimulus to innovators like Copernicus, they were not originally supported by the arguments that now make us believe them, and in the absence of these arguments they were rejected by most philosophers and almost all astronomers in the ancient world. In the Middle Ages they were ridiculed or ignored. The reasons for the rejection were excellent. These alternative cosmologies violate the first and most fundamental suggestions provided by the senses about the structure of the universe. Furthermore, this violation of common sense is not compensated for by any increase in the effectiveness with which they account for the appearances. At best they are no more economical, fruitful, or precise than the two-sphere universe, and they are a great deal harder to believe. It was difficult to take them seriously as explanations.

All of these alternative cosmologies take the motion of the earth as a premise, and all (except Heraclides' system) make the earth move as one of a number of heavenly bodies. But the first distinction suggested by the senses is that separating the earth and the heavens. The earth is not part of the heavens; it is the platform from which we view them. And the platform shares few or no apparent characteristics with the celestial bodies seen from it. The heavenly bodies seem bright points of light, the earth an immense nonluminous sphere of mud and rock. Little change is observed in the heavens: the stars are the same night after night and apparently have remained so throughout the many centuries covered by ancient records. In contrast the earth is the home of birth and change and destruction. Vegetation and animals alter from week to week; civilizations rise and fall from century to century; legends attest the slower topographical changes produced on earth by flood and storm. It seems absurd to make the earth like celestial bodies whose most prominent characteristic is that immutable regularity never to be achieved on the corruptible earth.

The idea that the earth moves seems initially equally absurd. Our senses tell us all we know of motion, and they indicate no motion for the earth. Until it is reëducated, common sense tells us that, if the earth is in motion, then the air, clouds, birds, and other objects not attached to the earth must be left behind. A man jumping would descend 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.

2

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