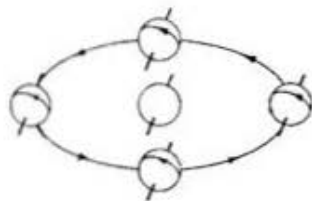


THE COPERNICAN REVOLUTION

Planetary Astronomy in the Development of Western Thought



THOMAS S. KUHN

HARVARD UNIVERSITY PRESS • CAMBRIDGE,
MASSACHUSETTS, AND LONDON, ENGLAND

1

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 pre-

dicting 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 non-scientific 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.⁹

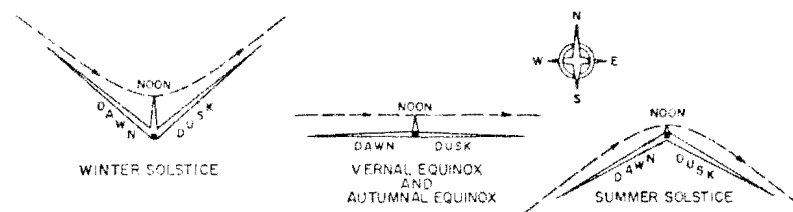


Figure 1. The daily motion of the gnomon's shadow at various seasons in middle-northern latitudes. At sunrise and sunset the shadow stretches momentarily to infinite distance where its end "joins" the broken line in the diagram. Between sunrise and sunset the end of the shadow moves slowly along the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

⁹ 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.

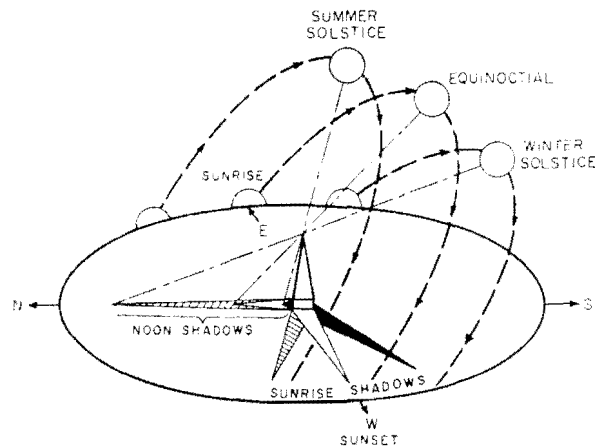


Figure 2. Relation between the position of sunrise, the sun's noon elevation, and the seasonal variation of the gnomon's shadow.

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 365 $\frac{1}{4}$ 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 365 $\frac{1}{4}$ 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

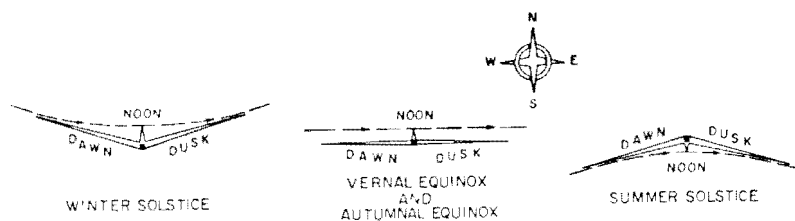


Figure 3. The daily motion of the gnomon's shadow at various seasons in the northern torrid zone.

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-

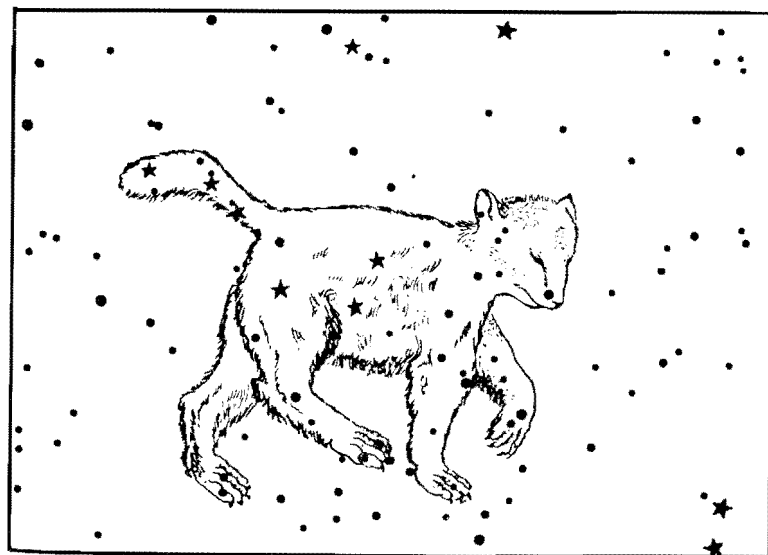


Figure 4. The constellation Ursa Major in the northern skies. Notice the familiar Big Dipper whose handle forms the bear's tail. The North Star is the prominent star directly over the bear's right ear in the picture. It lies almost on a line joining the last two stars in the Dipper's bowl.

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

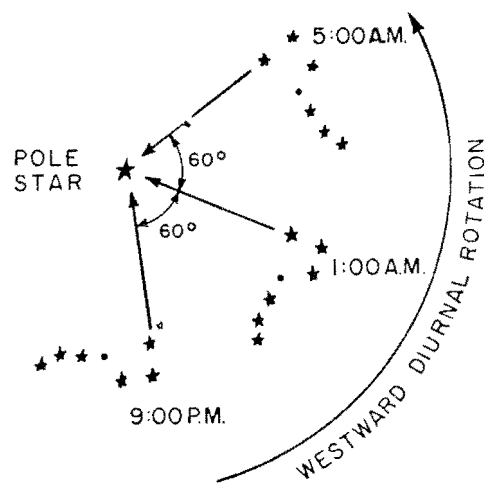


Figure 5. Successive positions of the Big Dipper at four-hour intervals on a night in late October.

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 7a), 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 7b). 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

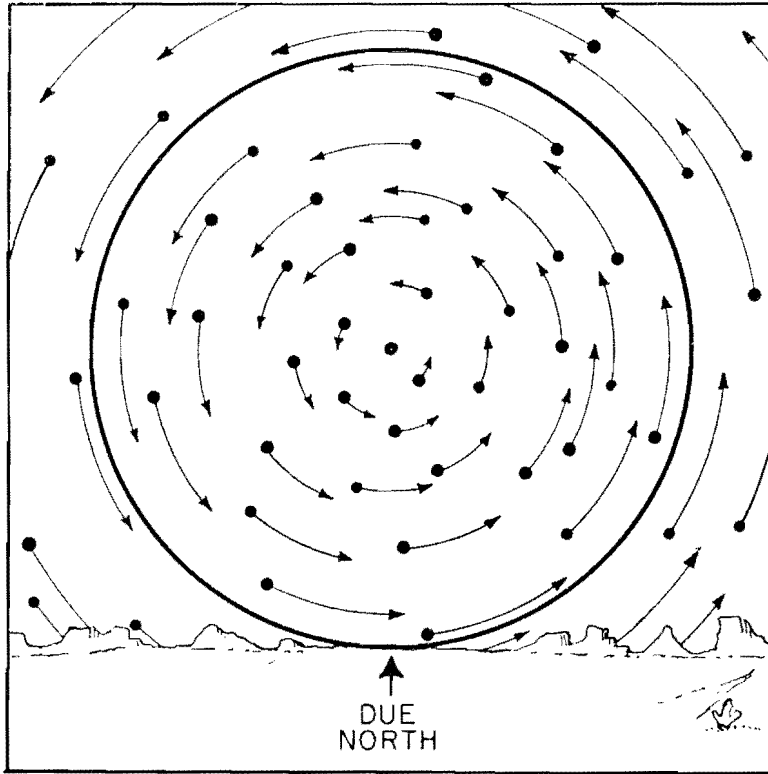
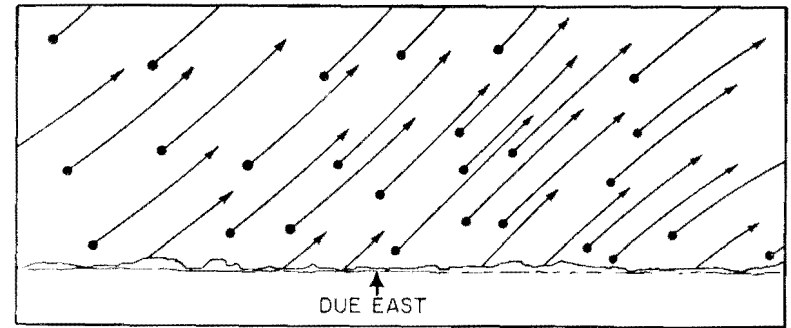


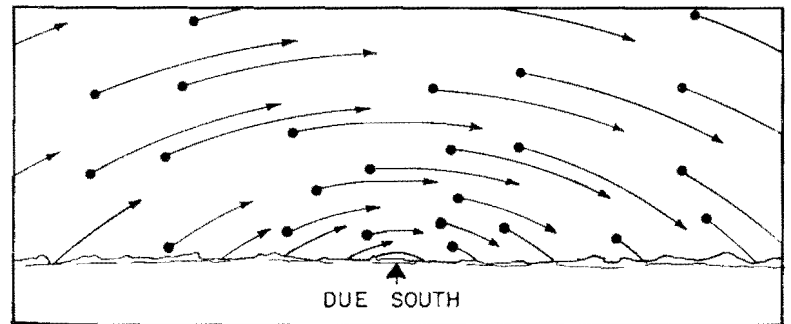
Figure 6. A set of the short circular arcs described by typical stars in the northern sky during a two-hour period. The heavy circle tangent to the horizon separates the circumpolar stars from those that rise and set.

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 7a 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-



(a)



(b)

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

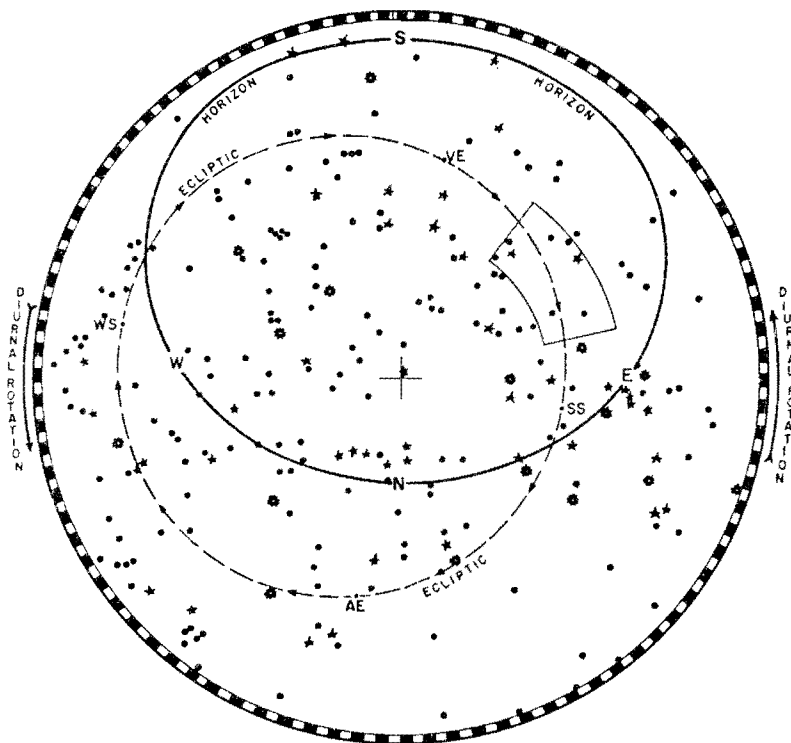


Figure 8. A circumpolar star map containing all the major stars ever visible to an observer at approximately 45° northern latitude. The cross at the geometric center of the map indicates the position of the celestial pole.

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

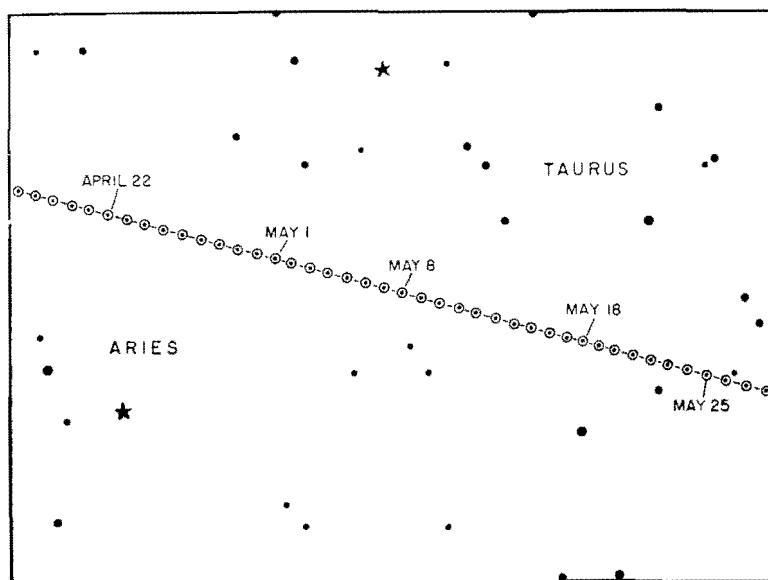


Figure 9. Motion of the sun through the constellations Aries and Taurus. The circles represent the sun's position among the stars at sunset on successive evenings from the middle of April to late May.

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 Chapter 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 inter-

pretation 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