CHAPTER 1

The Observed Motions of the Stars and the Sun

1. Science, Key to the Future, Has its Roots in the Past

The future, someone has said, belongs to those who embrace it. It belongs to those for whom it is a great and welcome adventure – not to the timid, nor to those who persist in looking regretfully back to some Golden Age. But the explorer who plunges heedlessly forward into unknown country invites disaster. So, in these times of swift and bewildering change, we all do well to greet the future with courage, but with our eyes wide open.

It is not easy for everyone to face a future which at best is sure to contain much that is unfamiliar and uncertain. What seems good to one may be unbearable for another; many long for reassurance and become obsessed with the desire for security. We must resist this mood, which can only lead to failure. As we move resolutely ahead, knowledge and understanding can be summoned to our support. Knowledge of the basic laws of nature, which do not change and which always stand ready to be our allies, is preparation for life in an era of explosive scientific and technologic change. To know something of the vocabulary of science and to appreciate, even dimly, the struggles through which the scientific enterprise has evolved, is to escape from the fear of the unknown, so often associated with science in the minds of the nonscientific public. Such knowledge and appreciation are essential for a full understanding of the problems of contemporary society and, so to speak, prerequisite to full membership in that society. It is for such reasons that education in science takes on high significance in the present era of world crisis.

Science, as we all know, is knowledge of natural law. In another sense of the word, it is a social phenomenon and a key factor in the flux of present-day civilization. To say that science makes the difference between the twentieth century and the tenth, between the culture of contemporary North America and that of contemporary Indonesia, is to oversimplify, but the assertion points to a fundamental truth. Science and scientific technology have changed and are changing our homes, our factories, and our farms. They are transforming the whole structure of our society. Scientific discovery reaches into our minds in ways that are direct and indirect, ways that change the manner in which we think of ourselves and the universe around us, ways that subtly alter our hopes and fears and our standards of value.

Scientific discovery gives us, first of all, an every deepening understanding of the processes of nature. With this new understanding an unending stream of new technological possibilities becomes available. As economically advantageous possibilities are converted into actualities, our technology and the environment in which each one of us works out the pattern of his life are continuously transformed. The pace of the transformation becomes more rapid year by year. Never before has society supported so many scientists and engineers. Never before has there been such a partnership between scientists and technologists as that achieved in the great research laboratories of today. The leaders of the great nations have made the momentous discovery that technological exploitation of advances in science is a key to economic and military power. Whether we like it or not, we find ourselves driven by economic pressure and international rivalry into a scientific and technological race.

In these circumstances one cannot doubt that the immediate future will be a period of continued high-speed technological evolution. It will also be a period of continual stress for the individual struggling to adjust his own life to a changing environment and for society as a whole in its institutional response to new knowledge, new economic patterns, and rising population densities. Fresh powers of imagination and collective wisdom will be needed to convert technical advances into long-range human values. In the future, as now, we will have to face grave international problems arising in large part from the desire of technologically backward nations to share in the material advantages that advanced technology has brought to Europe and North America. Throughout the world, forces generated by the progress in physical, biological, and social sciences may be expected to grow in importance. Therefore, if we are to understand the future and carry our share of its responsibilities, we will need to know something of the achievements, limitations, and language of science. We all need to appreciate the nature of scientific progress and to share in the flexible and tentative spirit with which scientists have learned to pursue their inquiries.

But it would be a mistake to let preoccupation with the future close our eyes to history. We foresee by remembering. To look ahead is to use past experience as a guide to the future; there is no other guide. To be sure, most scientists have little enthusiasm for history. The job of the scientist is to make discoveries and develop new ideas. When new ideas prove effective they tend to make old ones obsolete: thus it is not altogether unfair to say that the typical scientist is in the business of creating the future and destroying the past.[1] Nevertheless, science has a proud past of its own, extending back to ancient Greece. In the light of that past an extra dimension is added to the scientific knowledge of today.

Science is primarily a way of investigating the timeless regularities

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[1] Cf. Howard Mumford Jones, "A Humanist Looks at Science," *Daedalus*, Winter issue, 1958. Jones apologizes for his dig at the scientists, but they can enjoy it as well as he.

of nature. Because these regularities are timeless, they can be checked here and now by direct observation and experimentation. They are not mere hearsay. The ultimate authority in science is the fact of observation. Hence, it is important for the student of science to get first-hand experience with his own eyes and his own fingers in the laboratory. The present state of scientific knowledge can be taught to the beginner by demonstration and mathematical argument in such a way that it divorces the subject from its history. This procedure has come to be the accepted practice because it is congenial to the mind of the average scientist of today, intent as he is on speeding up the education of the next generation of scientific investigators. It is, nevertheless, a procedure with distinct disadvantages that should not be overlooked.

To disregard the history of science and the human meaning of the scientific enterprise is to cut off the part of the story most appealing to students whose interest is not professional. It dehumanizes the subject and contributes to the perpetuation of the antagonisms that too often separate scientists from humanists. It ignores the sense of deep satisfaction that many students find when they are able to join a clear comprehension of abstract scientific principles with an appreciation of the struggles through which our understanding of those principles has evolved.

This introduction to physical science takes a different course, based on the conviction that by uniting a rigorous study of the basic scientific conceptions with a historical and human context we can make it more interesting to most students and more meaningful to all. In the view of the author, the scientific enterprise has essential contributions to make to our standards of value and to our power to discriminate between truth, half-truth, wishful thinking, and mere conjecture. We hope in some degree to make these contributions available to our readers.

The early history of science is of special interest to nonscientists, because it reveals the profound influence of scientific conceptions on the way men have thought of themselves and the universe about them. The first emergence of ancient man from the capricious, spirit-ridden world of primitive animism into a lawful universe which he could hope to understand took place among the Greeks of classical antiquity. After the Dark Ages, the Middle Ages, and the Renaissance, a second great period of scientific activity in the sixteenth and seventeenth centuries succeeded in transferring the seat of authority from the pages of Aristotle to the quantitative observation of the facts of nature. There were heroes in those days, and the accounts of their struggles against the authority of tradition are as illuminating as they are interesting.

Fortunately, the order in which the basic ideas of physical science were developed is well suited to the needs of beginning students. Science itself began as an extension of common sense, based on a mathematical analysis of simple and repeatable elements in everyday experience. Today scientists have opened up a greatly enlarged world of experience by the invention of instruments that allow us to explore phenomena previously undreamed of. Scientific theory is a logical structure which binds the world of everyday experience and the new world revealed by our instruments into a single, self-consistent, and intelligible whole. Unfortunately, as scientific knowledge has grown it has become increasingly abstract and increasingly difficult to understand without the help of advanced mathematics. Because it is obviously powerful, largely incomprehensible, and frequently paradoxical, science is viewed by many of the uninitiated as a form of magic. In these circumstances the arrangement of topics in an introductory scientific textbook in a historical, or quasi historical, order has distinct advantages. This order begins with the origins of the scientific enterprise and lends emphasis to the common-sense roots from which that enterprise evolved. It helps the teacher to avoid scientific authoritarianism and helps the student to keep his feet on the ground. In these volumes we follow the historical order in a general way, combining scientific exposition with elementary historical and philosophical material calculated to bring out the wider meaning of major scientific achievements. In pursuing our basic objectives we have welcomed the opportunity to give variety to the text by shifting the point of view, style, and difficulty from chapter to chapter and section to section.

2. The Origin and Nature of Science

2.1. Today a mental gulf separates the typical scientist from the typical manual worker whose activities provide us with food, clothing, housing, and other goods and services. Historically, however, science may be regarded as an outgrowth of the practical activities of primitive men in their struggle to wring the necessities of life from the world about them. Men have become masters of the earth by developing new tools and techniques with which to meet their physical needs and do battle with their enemies. Every tool and every technique is a means for utilizing some law of nature to accomplish a practical purpose. In a sense each tool and each routine of procedure embodies recognition of elementary natural law. This relation is obvious, for example, in the sowing and reaping of crops, the cooking of food, the sawing of wood. It was not until men had reached a high degree of civilization, however, that they realized the possibility of describing in words and other symbols those constant characteristics of the behavior of the universe (i.e., laws of nature) that made their tools and techniques effective. The development of new methods and of language, with its power to classify objects in abstract terms, went hand in hand for ages before the Greeks began the formulation of natural laws of a coherent and general character. To quote Benjamin Farrington, "Men were weighing for thousands of years before Archimedes worked out the laws of [mechanical] equilibrium; they must have had practical and intuitional knowledge of the principles involved. What Archimedes did was to sort out the theoretical implications of this practical knowledge and present the resulting body of knowledge as a logically coherent system."[2] The disentangling of general laws from practical experience can be regarded as the beginning of science as we usually understand the term today.

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[2] Benjamin Farrington, *Greek Science* (Penguin Books, Ltd., Harmondsworth, England, 1944), Vol. 1, p. 20.

2.2. Since the age of Archimedes the interactions between theoretical science and the activities of everyday life have continued to grow in importance. The inventions of practical men have called the attention of scientists to phenomena that deserve analysis. They have provided scientists with materials, tools, and techniques for experimental research. Conversely, the systematic development of the concepts and laws of pure science has stimulated invention and made possible the design of elaborate and delicate industrial operations that could not have been worked out in any other way.

Today our great governmental and industrial laboratories are organized to make the most of a fusion of scientific and technological know-how. The parade of wonders made possible by large-scale cooperation of scientists and technologists, working with lavish financial support,[3] is the key factor in today's struggle for economic growth and military power. An advanced technology provides scientists with a wealth of precision tools both small and large with which to carry on their investigations. At the same time the scientists provide the engineers and industrialists with a detailed understanding of physical and chemical phenomena on which to base the design of new products and new methods of fabricating them. "Human knowledge," said Francis Bacon in 1620, "and human power meet in one; for where the cause is not known the effect cannot be produced. Nature to be commanded must be obeyed." It is to the realization of the truth of Bacon's words, in conjunction with immense natural resources, that we owe the wealth, industrial power, and progressive character of our western civilization.

2.3. In view of the long-standing and intimate connection between theoretical science and technology it should be clear that in a sense the daily activities by which the savage keeps alive, the activities of those who plan and those who execute the work of modern industry, and the activities of the pure scientist are all of a piece. To divide these activities into separate categories is somewhat artificial and arbitrary. From this point of view it makes sense to define natural science inclusively as "the system of behaviour by which man acquires mastery over his environment."[4] Such a definition includes all technology, primitive and modern, and all that a child learns as he first explores the world about him and masters in succession the arts of walking, talking, and doing arithmetic. The conception has fascination because of its stress on the unity of a vast range of activities. And of course it appeals particularly to the Marxist with his insistence on the economic interpretation of human behavior.

2.4. On the other hand, this broad definition goes beyond the limited scope of these volumes. We shall therefore make use of the more restricted traditional definition given in the dictionaries, which say that science is an organized and tested body of knowledge based on exact observation. This is the primary and most generally

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[3] Leonard S. Silk, *The Research Revolution* (McGraw-Hill Book Co., New York, 1960).

[4] J. G. Crowther, *Social Relations of Science* (The Macmillan Co., London and New York, 1941), p. 1.

accepted interpretation of the word, which comes from *scientia*, a Latin root meaning "knowledge." The term "science" is used also to refer to the *process* by which scientific knowledge grows – the exploration of the universe, in which the community of scientists is engaged. From this second point of view it will be convenient to adopt the following explicit basic definition: *Natural science is the conscious and systematic application of man's intelligence and ingenuity to the discovery of the laws that regulate the universe of nature.*[5] Science, so defined, is the activity known today as "basic science" or "pure science."[6]

This second definition of natural science excludes mathematics, which began with the study of numbers, magnitudes, and logical relationships, because mathematics as we understand it today is not directly concerned with the universe of nature. Since mathematics is the search for a kind of exact knowledge, we can include it in the broad general category of science, but it is not a science of nature.

Our definition excludes also the unconscious learning of the child and the unsystematic invention of tools and techniques by primitive men. It excludes even the application of scientific laws to the design of the machines and instruments of modern technology. From our present point of view, natural science is a human enterprise whose primary goal is to achieve an understanding of nature through the accumulation of an organized body of knowledge of natural processes.

In making these exclusions we have no desire to play down the importance of the practical applications of science to society, nor do we intend to exclude discussion of all applications from these volumes. We do, however, wish to focus our primary attention on the nonutilitarian activity commonly known as basic science. We shall be concerned chiefly with physics, chemistry, and astronomy and not with refrigerators, television sets, airplanes, or rockets. In making this choice we recognize that between such men as Galileo, Newton, Maxwell, and Einstein, working to expand the limits of human knowledge, and others, such as Watt, Marconi, the Wright Brothers, Edison, and Steinmetz, who have contributed primarily to the advancement of technology, there have existed differences in motivation and in values. The problems of science are set by the interests and intuitions of scientists for whom every step is a choice between alternatives. The choices of inventors and engineers are quite different from those of pure scientists, even when both are involved in the same general area of scientific activity. Thus it is important to make the distinction between pure science and applied science as well as to realize the intimate relation that can exist between them.

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[5] A law of nature is merely a description of what we observe to happen in certain appropriate circumstances. A typical law is the rule that "if a ray of light strikes the polished surface of a mirror, the reflected ray makes the same angle with the surface as the incident ray." Although we say that such laws regulate nature, we are *not* to regard them as rules imposed by an ineffable external authority, but as exact statements of what all qualified observers have seen in rigorous tests, repeated many times over many years, when they have looked at the given phenomena under identical appropriate conditions.

[6] In 1963 only about ten percent of the total annual expenditures for research and development in the United States was used for basic science.

One final point should be made in this initial characterization of our subject matter. Experience has shown that by the construction of theories we can bind our knowledge of natural law into a logically organized structure based on a limited number of hypotheses, or fundamental assumptions. Such a structure is infinitely more satisfying and meaningful than a mere catalogue of unrelated laws. Moreover, it stimulates the mind of the scientist and so leads him on to the discovery of new facts and relationships. For these reasons we include as an essential part of our conception of science the construction of coherent theories that interpret and unify our knowledge of natural law.

3. The Classification of the Sciences

3.1. Included within the general domain of fundamental science in addition to the natural sciences and mathematics are the *social sciences*, i.e., anthropology, social psychology, sociology, government, economics, and history. These are all concerned with human society and its problems. They are similar to the natural sciences in objectives and spirit but are by tradition excluded from the list of natural sciences, perhaps because in the past human society was not considered to be a part of nature.

The natural sciences include the *physical sciences*, e.g., astronomy, physics, chemistry, and geology, with their subdivisions, and the *biological sciences*. In contrast to the biological sciences, the physical sciences deal with relatively simple questions — difficult enough but easier to get on with than those that face the biologist. Because of this great difference in complexity the physical sciences have developed more rapidly and have grown mathematical, whereas the biological sciences until recent times were predominantly descriptive. For a long period of time biologists were chiefly concerned with the identification and naming of the different species of plants and animals and with qualitative observations regarding their habits — with what we now call natural history. The basic laws of chemistry were not properly straightened out until about a hundred years ago; only then was the way open for the development of a deeper understanding of genetics and the physiology of living organisms.

In addition to mathematics and the fundamental natural and social sciences there exist a variety of *applied sciences*, including various branches of engineering, scientific agriculture, and medicine. These are all concerned with the application of scientific knowledge and scientific methods to the solution of problems in the practical arts. It is convenient to make a distinction between these and the pure sciences, although it frequently happens that men engaged in the study of applied science attack and solve problems in a related field of pure science. The study of aeronautics, for example, has led to important advances in the branch of pure physics that deals with the flow of compressible fluids.

The truth is that the different sciences are not separated by clean-cut distinctions. The interests of scientists trained as physicists, chemists, geologists, and astronomers overlap. For this reason many problems can be attacked with profit by research workers from two or more of these fields. The names of the special sciences are a convenience of historical origin, but a precise separation of these areas of investigation is not possible.

3.2. *Mathematics* has played a central part in the development of the physical sciences but is not included in the list of such sciences, because present-day mathematicians regard their subject as an abstract study of quantitative relationships and, more generally, of the business of drawing inferences from systems of postulates. Modern mathematics is in fact inseparable from formal symbolic logic. We reckon it a science because it leads, like the other sciences, to a practically verifiable and accumulating body of knowledge. But this knowledge has to do with a mental world of symbolic relations and is independent of physical observation or experiment. It is true that mathematics is important to the natural scientist because he finds in nature entities that conform to the definitions and postulates of mathematics, but the pure mathematician is not directly concerned with physics or chemistry. These subjects are fields in which mathematics is *applied*, just as physics and chemistry are applied in the engineering sciences.

3.3. The basic natural sciences, together with mathematics, can be arranged in a consecutive order in which each depends to a large extent on the sciences that precede it, but very little on those that follow. That order is: mathematics, physics, chemistry, biology. Astronomy and geology are studies of particular physical systems, and their laws do not have the generality of the laws of mathematics, physics, and chemistry. Therefore they can be regarded as fields of application of mathematics, physics, and chemistry, rather than as independent basic sciences.

From this point of view physics is the most fundamental of the sciences of nature. Since no introductory text of reasonable size can hope to give an adequate account of any of the physical sciences if it tries to deal impartially with them all, we assign a central position in this book to physics. Historically, however, physics did not develop as early as mathematics and astronomy.

4. The Beginnings of Mathematics

4.1. In the beginning came mathematics. Of course, mathematics is still developing. The sciences march abreast. But mathematics was the first science to establish itself on solid ground. It was needed in the daily life of the earliest civilizations. Without its aid the other basic sciences would have been stillborn. Mathematics is not a natural science, but we can confidently assume that it originated in the same matters of practical necessity that brought forth the natural sciences. It was the prerequisite for exact thinking about the physical world, and in turn it was vastly stimulated by the needs of the physical sciences as they developed.

The simplest mathematical technique is *counting*, an operation important to the most primitive savages. Community life required the counting of warriors, wives, and flocks. Counting meant the invention of words and, ultimately, written symbols for the various cardinal numbers. With barter and the arts of civilization came the need for a compact notation for large numbers, for addition, subtraction, and the other operations of elementary arithmetic. The story of the development of methods for recording and handling numbers can be followed in part from the records of the

Sumerians and the other ancient civilizations in the river valleys of Mesopotamia, India, and Egypt. Progress was necessarily slow and fumbling, for the ancients could have no premonition of the possibilities of a compact and convenient notation for numbers, such as we have today. Today arithmetic seems very simple, but the record of history shows that its appearance of simplicity is highly deceptive.

4.2. Like arithmetic, the second basic branch of elementary mathematics, *geometry* (land measurement), seems to have had its origin in the practical needs of the ancient world. The first important civilizations appeared in regions of low rainfall on the flood plains of great rivers. To establish these civilizations it was necessary to drain vast swamps and also to utilize the annual floods to irrigate the fields. An art of surveying was needed to reestablish the boundaries of fields after the subsidence of flood waters. Our information about this early chapter of scientific history is very meager, but we know that the Babylonians and Egyptians had a practical knowledge of geometry. The presumption is that the geometrical rules they used were developed for the guidance of surveyors and builders. Their temples and pyramids were accurately laid out and indicate a high degree of geometrical skill.

The development of geometry as a logically connected system of general theorems based on a few simple definitions and axioms did not come until the time of the Greeks. The work was begun by Thales of Miletus (*c.* 624–565 B.C.), the first great philosopher-scientist of the Greek school. It was carried forward by Pythagoras (born *c.* 582 B.C.), Plato (427–347 B.C.), and others, reaching its culmination in the writings of Euclid (*c.* 330–*c.* 260 B.C.).

4.3. To speak of the beginnings of geometry in a book on physical science raises a question of some subtlety. From the time of Euclid until the nineteenth century it was generally assumed that Euclid's axioms, or an equivalent set, must necessarily hold for the geometry of physical space — i.e., for the geometry of rigid bodies and light rays. The basic theorems of Euclid's geometry are supported by experiments performed with material bodies. Although such experiments have only a limited accuracy, the agreement between observation and theory was considered good enough to justify the notion that the theory and the experimental truth are one and the same. At this point, then, mathematics and physics seemed identical.

Early in the nineteenth century, however, Lobachevski and others demonstrated the possibility of mathematical geometries based on axioms contradicting those of Euclid. With this discovery it became evident that one must make a distinction between mathematical geometry and physical geometry. Only experiment can decide which, if any, of the mathematical geometries fits the facts of physics. More recently the analysis of Einstein and the experimental discovery that light rays bend a little in the neighborhood of the sun have led to the general acceptance by competent scientists of the view that the physical geometry of large-scale figures is not rigorously Euclidean. Although, for example, the sum of the measured angles of a plane triangle whose sides are no more than a few miles long is so nearly equal to 180° that we cannot detect the difference, we should not assume that this Euclidean result would hold if we could make the test with a triangle whose corners are located on stars separated by distances of millions or billions of light-years.

Fortunately, the astronomers of ancient Greece had no inkling of such a confusing possibility. Without misgivings they could apply Euclid's geometry to their observations of the stars and deduce a picture that satisfied instinct while creating a pattern for more rigorous subsequent investigation.

5. The Apparent Motions of the Stars

5.1. In speaking of the motion of bodies on or near the earth's surface, we all instinctively think of the earth as without motion and at rest. What other standard of motionless behavior could we have? So, from our everyday common-sense point of view, a body is reckoned at rest or in motion, according to whether its position relative to the earth's surface is fixed or changing.

If we stick to this common-sense point of view as we watch the sun and stars rise in the east, sweep across the sky, and set in the west, we are bound to conclude that these heavenly bodies revolve about the earth. This was the inevitable opinion of ancient man. His universe was centered on the fixed earth on which he lived.

Schoolchildren today are commonly taught, however, that the sun and stars are actually at rest, while the solid earth beneath our feet spins through space and causes the illusion of motion in the sky. One can quibble with this statement, but it will serve for the moment to describe the modern moving-earth interpretation of the basic geometrical facts of astronomy. This interpretation goes back to the Greek astronomer Aristarchus of Samos, who lived about 250 years before Christ, but it did not gain widespread acceptance until the seventeenth century.

The story of the evolution of the moving-earth interpretation from the earlier fixed-earth interpretation is the central story of the origin of modern science and the primary theme of the early chapters of this volume. It is a story of the painstaking accumulation of geometrical observations over many centuries, of repeated attempts to interpret these observations in terms of simple mathematical laws, and of the ultimate triumph of mathematical analysis over common sense. The last dramatic stage in the historical sequence is called the *Copernican Revolution* (cf. Chap. 4). Its human significance is hard to exaggerate.

To tell this story properly we must begin with the facts of observation and the early attempts to interpret them. The facts of observation have to do with the motions of the heavenly bodies relative to the earth. With due regard to the ultimate advantage of choosing the sun and stars as our standard of rest, we refer to the directly observed motions relative to the earth as "apparent motions." This way of speaking does not mean, however, that the motions are illusory. They are, in fact, the basic data of all astronomical understanding.

5.2. Consider first the simple elementary facts about the positions and motions of the stars relative to one another and to the earth. The stars sweep across the sky during the night in the same general east-to-west direction as the sun, the moon, and the planets. Despite this motion the angular distance between each pair of stars remains constant. Each constellation rises and falls in the course of the night, but the relative positions of its members are fixed, so that the constellation presents to the eye an unchanging pattern.

As one looks into the sky at night, the "vault of heaven" appears as a vast hemispheric canopy stretched overhead. We know today that this canopy is an illusion; the stars are not all equidistant from the earth as the points on such a canopy would be. But they are all so far away that without instruments of the greatest refinement it is impossible to measure the distance to any of them. Their apparent positions are unaffected by differences in distance, and we do no violence to what we see if we think of the stars as spread out on a great *celestial sphere*, with the earth at its centre. This imaginary sphere must be supposed so vast that the earth itself is to be regarded as a mere speck or point in comparison. For us the celestial sphere is an imaginary concept of value because we find it convenient to lay out star maps on small models of this sphere. The ancients, however, supposed it to be a physical reality.

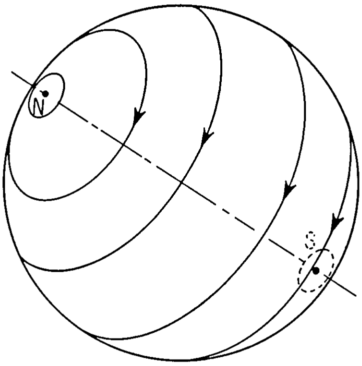

Fig. 1–1. *The Apparent Motion of the Stars, Illustrated by the Rotation of a Globe on a Diameter as Axis.* As the globe turns on an axis through *N* and *S*, points on the surface of the globe move in parallel coaxial circles. *N* and *S* are called the poles of the motion.

5.3. Since the stars can be represented as points on a rigid spherical surface, their individual motions must be compatible with some possible motion of such a surface. The simplest possibility consistent with the fixed position of the earth at the center of the celestial sphere is a uniform rotation about a fixed central axis, or diameter (Fig. 1–1). This suggestion fits the facts very closely.

In such a motion all points move in parallel coaxial circles.[7] The axis of rotation of the celestial sphere passes through the earth and a point on the sphere not far from the bright star Polaris, commonly known as the "North Star" or "Pole Star." So stars in its neighborhood, if we watch them through the night, seem to rotate in circles about Polaris as a common center. The familiar Great Dipper sweeps about Polaris as if attached to a giant pinwheel. The impression is confirmed by photographic traces of star paths obtained by long exposures with a camera pointed toward Polaris. The traces (Fig. 1–2) are circular arcs whose common center marks the point at which the axis of rotation is conceived to pierce the celestial sphere itself. This point is designated as the *north celestial pole* (NCP). (The north pole of the earth is by definition the point on the earth's surface directly under the north celestial pole.) Polaris is actually about 2°, or four moon-diameters, away from the north celestial pole in a direction

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[7] The motion can be illustrated by spinning a geographic globe on its north-south axis. Each point on the surface then moves in a circle of constant latitude. To relate the motion of the globe to that of the stars one must remember, of course, that we see the globe from the outside but look at the stars from the inside of the celestial sphere.

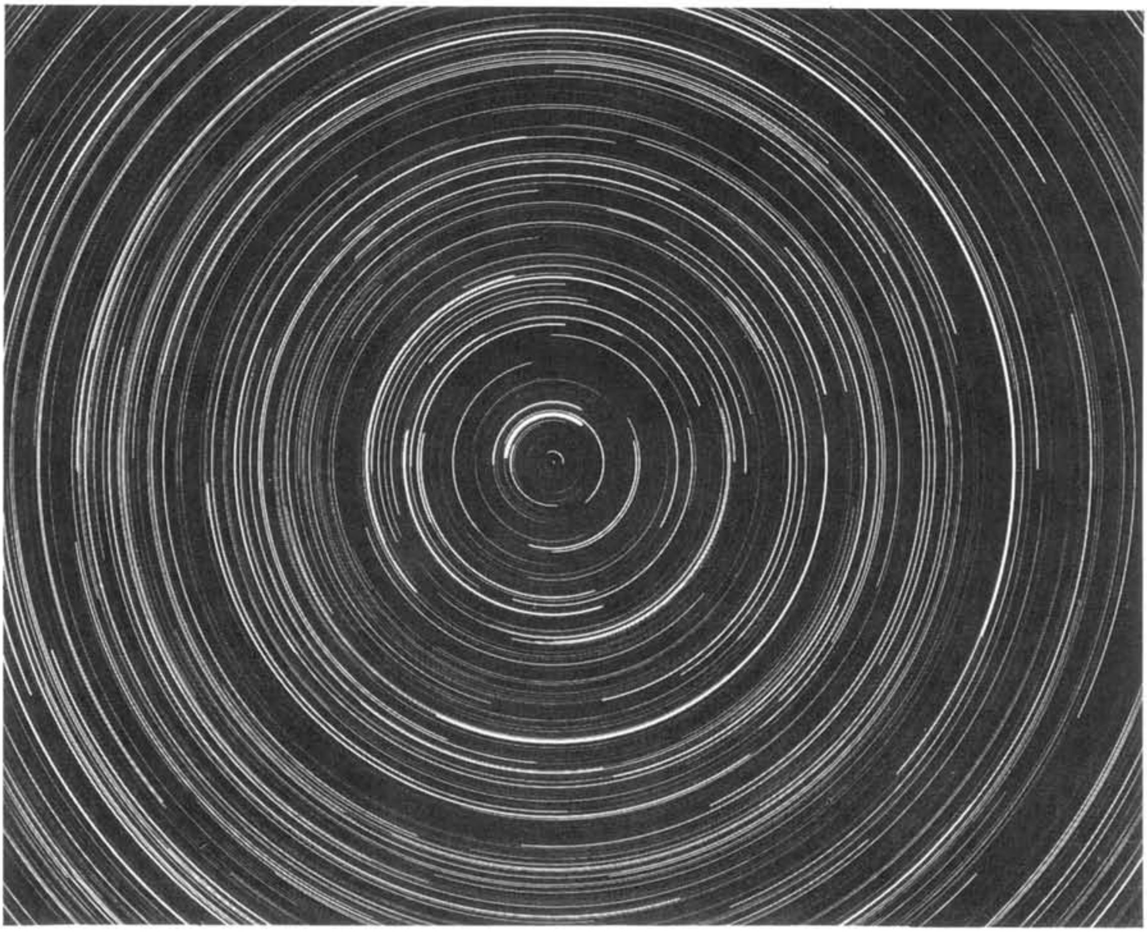


Fig. 1–2. *Star Trails in the Northern Sky.* This is a time exposure lasting about eight hours, made with a stationary camera. All traces are circular arcs centered on the north celestial pole. Note the short, heavy trace of Polaris near the center (Lick Observatory photograph).

away from the Great Dipper and toward the bright constellation of Cassiopeia. So Polaris rotates with the other stars, but since the circle is small and there is no star to mark its center, Polaris seems to be stationary — the one relatively fixed observable point in the sky by which sailors have for centuries set their courses.

The traces of the paths of stars remote from Polaris, as seen by observers in the north temperate zone, are curves that originate on the eastern horizon and sweep overhead to the western horizon. The camera can pick up only a small part of such a path in a single exposure. Because our point of observation on the earth is always close to the center of the circular path of any star near the celestial equator (the great circle 90° south of the north celestial pole) the trace of such a star, like a piece of the horizon, is seen as a straight line.

5.4. Observers in the southern hemisphere do not see the North Star, which lies below their northern horizon, but they can see a second fixed center of rotation to the south, the *south celestial pole* (SCP) 180° away from the north celestial pole. There is no bright star near this second pole; it is only by accident that the north celestial pole is conveniently marked by the neighboring bright Pole Star. *The axis of rotation*, or *polar axis*, of the celestial sphere is the straight line joining the north celestial pole with the south celestial pole. Since the observer always seems to be at the center of the celestial sphere, he seems to be on the axis of rotation wherever he may be on the earth's surface and whatever the time of year.

5.5. At any given point on the earth's surface the angular elevation of the north pole of the celestial sphere above the northern horizon, or of the south pole of the celestial sphere above the southern horizon, is always the same. Moreover, the vertical plane through the celestial poles and any terrestrial observer intersects the earth's surface in a fixed north-south line. Thus the celestial poles and the direction of the celestial axis of rotation are fixed with reference to the earth as well as with reference to the stars. In fact, we define the earth's axis as a line drawn through the center of the earth in the direction of the celestial axis.

5.6. In order to clarify completely these general, simple statements about the diurnal (daily) motion of the stars and to lay a foundation for the rest of our story, it is necessary to introduce a short technical vocabulary. Unlike poetry, which frequently appeals to our aesthetic sense through ambiguity and alliteration, physical science is a search for exact knowledge. The formulation of scientific theory requires the use of words with unambiguous definitions. Experimental science uses specialized techniques and instruments that must have names. So, to know what science is all about, we require a special vocabulary.

Let us observe, to begin with, that in order to locate any object in space we must have a *frame of reference* with which to compare it — some other object or set of objects that we think of as stationary. In everyday life, for example, it is convenient to think of the earth's surface as stationary and to define the geographical position of any point in terms of its *latitude* and *longitude*, angular distances measured from internationally established reference lines fixed on the earth's surface. In this case the earth is the frame of reference for geographical position, and the latitude and longitude are referred to as its *geographical coordinates.*

On the other hand, passengers on a ship, train, or airplane are likely to be interested in the relative positions of objects inside the moving vehicle; they therefore choose the rigid framework of the vehicle as their frame of reference, treating it as stationary for the purpose in hand. Thus frames of reference are arbitrary and should be chosen for convenience, with due consideration of the purposes of the user.

In modern astronomy a number of different frames of reference are useful, but it was natural for the ancient astronomers of Babylon, Egypt, and Greece to take the earth's surface as their frame of reference. Indeed, the modern observer with his huge telescope can make a direct observation of a star's position only by measuring the momentary angles between the line of sight to the star and reference lines that are fixed relative to the earth and the observatory. Thus the modern astronomer, like his ancient predecessor, must use the earth's surface as his primary frame of reference.

5.7. The natural lines of reference for an astronomical observer situated at a fixed point *O* on the earth's surface are a *vertical line* through *O*, a *north-south line* through *O*, and an *east-west line* through *O*. Figure 1–3 will help us to see how these lines are defined and established.

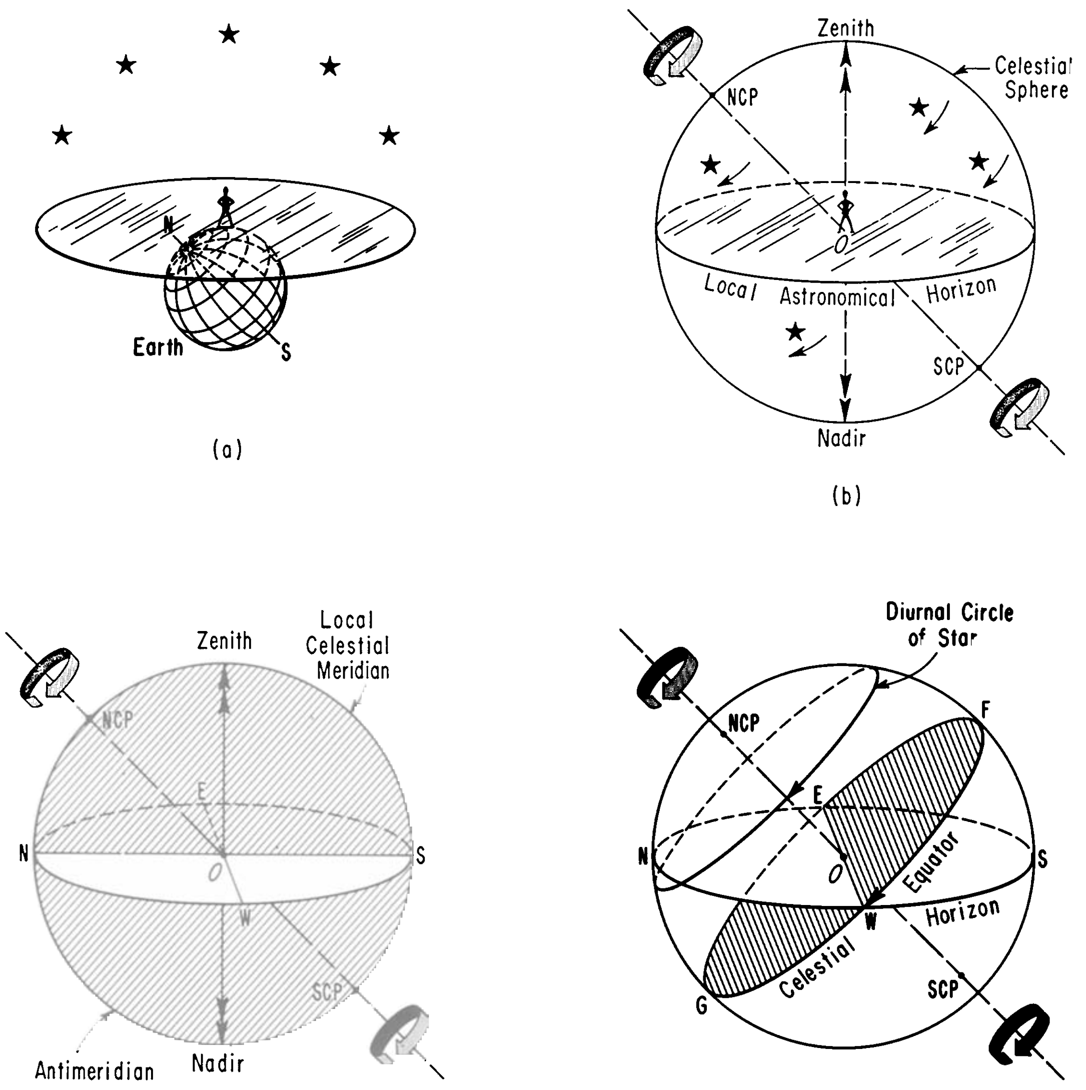
The direction of the *vertical* is fixed by the direction of a plumb line or by the perpendicular to a level liquid surface. The local *zenith* is the point straight overhead where the vertical through *O*, if infinitely extended, would pierce the celestial sphere. Beneath the observer's feet and directly opposite the zenith is the point at which the vertical extended infinitely downward from *O* would pierce the celestial sphere. This point is called the *nadir*. We assume for the present that the center of the earth is on the vertical between *O* and the nadir.

The *meridian plane* of the observer is a plane passing through his vertical and through the axis of rotation of the celestial sphere. In other words, it is that vertical plane through *O* that passes through the poles of the celestial sphere and hence very close to the Pole Star. The intersection of the meridian plane of the observer with the celestial sphere is an imaginary great circle of the celestial sphere that is called the *local celestial meridian*. It passes overhead from the north horizon to the south horizon through the celestial pole nearest to *O*. The lower half of this great circle is sometimes called the *antimeridian*.

The earth is so large that the surface of any large body of water seems flat. Actually it is curved, but for many purposes we can ignore the curvature and think of the astronomical observer as standing on a plane tangent to the earth's surface at *O*. This plane is called the *horizon plane*. Its intersection with the celestial sphere is called the *astronomical horizon*. The *visible horizon*, where sky and earth seem to meet, is close to the astronomical horizon, but its position varies with the topography of the land and the elevation of the observer.

The local north-south line through *O* is defined as the intersection of the meridian plane through *O* and the horizon plane. It must be determined by astronomical observations. The local east-west line in the horizon plane is drawn through *O* perpendicular to the north-south line.

5.8. The sequence of diagrams in Fig. 1–3 shows the earth, the stars, and the celestial sphere as seen from the outside. Diagrams of this sort, while very useful, always suffer from the disadvantage that the essentially infinite celestial sphere, at whose center we are placed, must be scaled down to a diameter of a couple of inches, while the spherical earth, if shown at all, must be relatively much too large. Thus, Diagram *a* shows the relation of the horizon plane to the earth, whereas in the following diagrams the oversize earth is removed (shrunk to zero size), leaving the observer on his horizon plane at the center of the celestial sphere. In all the



(a)

(b)

(c)

(d)

Fig. 1–3. *The Local Geographical Reference Planes and Lines.*

Diagram *a.* An observer stands on the earth, looking at the sky. For our purposes we may consider that he stands on his *local horizon plane*, tangent to the earth beneath him.

Diagram *b.* The stars move as if attached to a vast *celestial sphere* rotating about an *axis* that seems to pass through the observer and that meets the celestial sphere at the *north and south celestial poles* (*NCP* and *SCP*). The intersection of the horizon plane with the celestial sphere forms a great circle called the *local astronomical horizon.*

Diagram *c.* The plane drawn through the observer at *O*, through his zenith and the axis of the celestial sphere is called the *local meridian plane*. The *north-south line NS* is the intersection of the meridian plane with the horizon plane. The upper half of the great circle in which the meridian plane intersects the celestial sphere forms the *local celestial meridian.* The lower half of this circle is called *the antimeridian.*

Diagram *d.* A plane drawn at right angles to the axis of the celestial sphere through the observation point *O* cuts the celestial sphere along a great circle called the *celestial equator*. The intersection of the equatorial plane and the horizon plane forms the local east-west line *EW.*

diagrams it is assumed that the meridian plane of the observer is in the plane of the paper.

The celestial sphere rotates in a direction that carries the stars overhead from east to west. Each star moves along a circular path perpendicular to the celestial axis of rotation that joins the north celestial pole with the south celestial pole. These circular paths are called *diurnal circles* (Diagram *d*). A star is said to *culminate* when it reaches the highest point on its diurnal circle where that circle crosses the local celestial meridian. The closed curve *EFWG* on Diagram *d* represents the great circle on the celestial sphere perpendicular to the axis of rotation. We call this circle the *celestial equator*, in analogy with the earth's equator. The celestial equator would be the diurnal circle of a star that happened to be halfway between the north and south celestial poles. Since the plane of the celestial equator is perpendicular to the axis of the celestial sphere, it is perpendicular to the meridian plane. And since the horizon plane is also perpendicular to the meridian plane, the intersection of the horizon plane with the equatorial plane, by a theorem of solid geometry, is perpendicular to the meridian plane. It follows that *the equatorial plane intersects the horizon plane in the east-west line.*

The reader will note from Diagram *d* and from the argument of the preceding paragraph that a star on the celestial equator must rise due east of the observer and must set due west. Stars north or south of the celestial equator move in diurnal circles that decrease in size with decreasing distance from the nearer pole. In general, stars in the northern celestial hemisphere rise and set north of the east-west line, but the stars closest to the north pole (*north circumpolar stars*) are an exception to this rule, since they never sink below the horizon.

5.9. The angular elevation of the north celestial pole above the horizon varies with the geographic position of the observer. It is, in fact, equal to the *geographic latitude* of the observer (as you will see in Chap. 2) and increases from 0° to 90° as the observer travels northward from the earth's equator to the north pole. At the earth's north pole the north celestial pole is directly overhead, and all stars move in circles parallel to the horizon. In general, a star whose angular distance from the NCP is equal to the latitude of the observer describes a circular path in the sky which, at its lowest point, just touches the observer's northern horizon. Stars at slightly greater distances from the north celestial pole move in circles that cut below the horizon in short arcs in the north, while those at smaller distances remain above the horizon at all times.

5.10. The simplest methods of locating the north-south line and the east-west line depend on observations of the sun, whose path through the sky in any one day is similar to the diurnal circle of a star. The sun also reaches its maximum elevation above the horizon when it crosses the meridian plane. As it rises in the sky, the shadow cast by its rays falling on a vertical pole, or *gnomon*, becomes progressively shorter until the sun reaches the meridian. At that point the shadow has minimum length and is oriented along the north-south line because the sun's rays are in the meridian plane. Therefore, the direction of the shadow at the moment when it is shortest (noon by sundial time) can serve to fix the north-south line and thus also the east-west line.

A more accurate procedure is to use a *theodolite*, or *surveyor's transit*, a small portable telescope for measuring horizontal and vertical angles. The telescope has fixed "cross hairs" that permit accurate sighting on any object in the field of view. It is mounted so that it can be leveled and rotated about a horizontal axis *A* perpendicular to the telescope axis, or line of sight. The frame holding the axis *A* (Fig. 1–4) can be rotated in turn about a vertical axis *B*. Each axis has a scale to measure the corresponding rotation and a clamp to lock the axis at any desired position. If the telescope is rotated about *A* while the *B* clamp is locked, the line of sight sweeps out a vertical plane which we may designate as the *A* plane, or the vertical plane, of the telescope. The intersection of this plane with the celestial sphere is called a *vertical circle*. Rotation of the instrument about *B* gives the vertical plane any orientation desired.

The scale attached to the horizontal axis *A* can be used to measure the vertical angle between a star and the astronomical horizon. This angle is

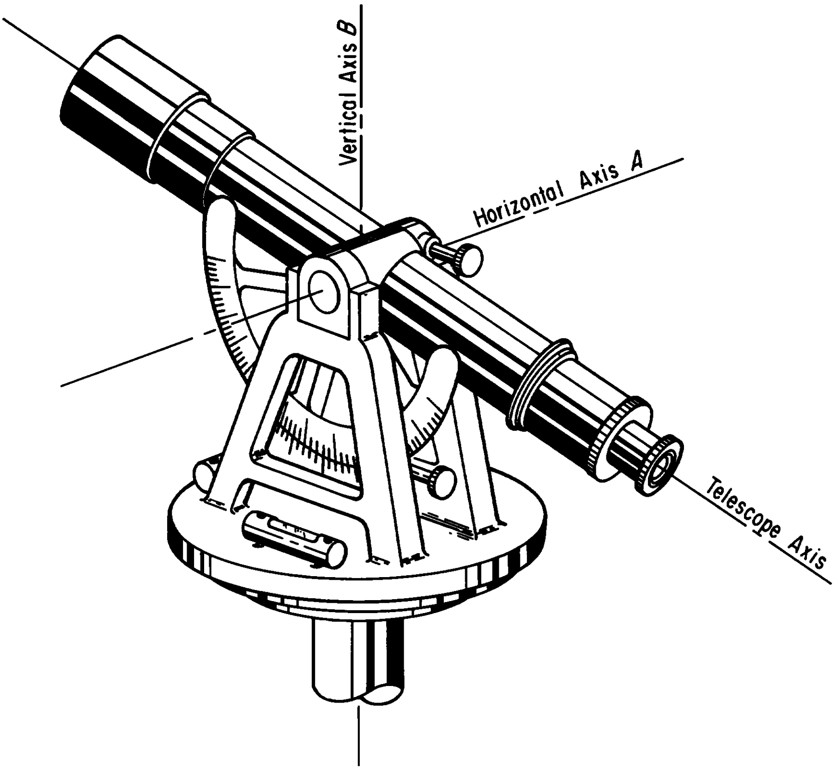


Fig. 1–4. *Simplified Model of Surveyor's Transit.* In this simple diagram many details are omitted. These include specifically scales for the measurement of horizontal rotation, clamps, and the tripod on which the instrument is usually mounted.

called the *altitude* of the star (Fig. 1–5).[8] Similarly, the scale attached to the vertical axis *B* can be used to measure the angle between the vertical plane of a star and the meridian plane. This latter angle is called the *azimuth* of the star.

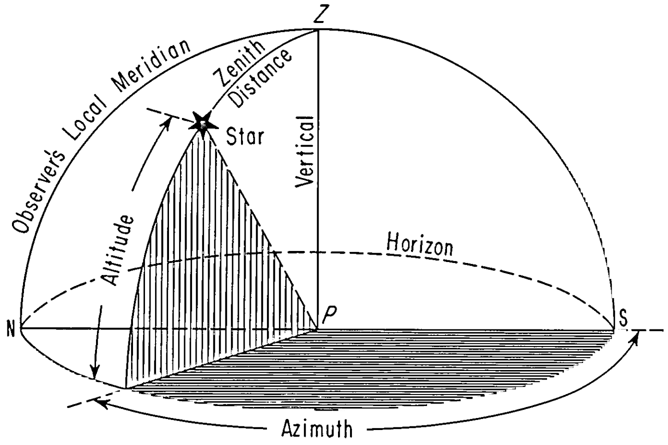


Fig. 1–5. *Altitude and Azimuth.* The *altitude* of a star is its angular distance above the horizon as seen by an observer at *P*. Its complement, the angular distance of the star from the vertical through *P* is called the star's *zenith distance.* Its *azimuth* is the angle which the plane of the star's vertical circle makes with the plane of the local meridian. Astronomers measure azimuth from the south point to the west around the horizon, but navigators measure it eastward from the north point.

To lay out a north-south line on the earth's surface with a transit, one must first level the instrument carefully and by observations of the stars set the *A* plane to coincide with the meridian plane. Then by turning the telescope toward distant points on the ground one can direct the setting of two or more stakes on the intersection of the meridian plane with the earth's surface. The essential problem accordingly is to locate the meridian plane by the stars. First, the telescope is aimed at Polaris and the sighting adjusted to fix the cross hairs on the star; then the accuracy of the sighting is refined by taking observations of Polaris before and after culmination. A precise location of the meridian plane by this method is not difficult and makes an interesting exercise in practical astronomy.

5.11. One of the important pieces of equipment in a modern observatory is the *meridian telescope,* or *astronomical transit.* The instrument is permanently mounted with a single east-west axis of rotation so that the line of sight can move only in the meridian plane. It is useful for measuring the time and altitudes at which different bodies cross the meridian plane.

The ancients had to sight without benefit of a telescopic lens and without accurately machined and calibrated telescope mountings. They could locate the north-south line and the east-west line with moderate precision, however, by observing either the circumpolar stars or the shift of the sunrise point with the seasons.

[8] The angle in radians subtended by a circular arc s at the center of the circle is s/r, where r is the radius of the circle. To convert radians into degrees we have to multiply by $360/2\pi$, or approximately by the factor 57.3° per radian. In geometrical astronomy we have much to do with angles subtended at the center of the celestial sphere by arcs of circles laid out in our imagination on that sphere. Every such angle is fully specified if we locate the circle and the ends of the arc in question. That being the case, it is customary to speak of such an angle as "measured along" a certain circle from an initial point A to a terminal point B. In this usage we say that the altitude of a star is measured along its vertical circle from the foot of that circle at F to the star itself. Similarly the astronomical azimuth is measured along the astronomical horizon from the south point westward to the point F.

6. The Daily and Annual Motions of the Sun

6.1. The second basic group of geometrical facts concerns the motion of the sun relative to the earth. This motion is more complicated than that of the stars and is best considered at first in terms of successive approximations. In first approximation the sun circles the earth like the stars, in the same direction and in about the same time. In second approximation, however, the sun is seen to move slowly among the stars. It lags behind the stars about one degree per day and at the same time travels back and forth across the celestial equator, moving north in the northern summer and south in the northern winter. Exact observations show that *relative to the stars* the sun follows a simple path on the celestial sphere that is practically fixed and has the form of a great circle. We call this great circle the *ecliptic* because eclipses of the sun and moon occur only when the moon is crossing it. The annual north-south migration of the sun is due to the fact that the plane of the ecliptic is inclined at an angle of $23\frac{1}{2}°$ to the plane of the celestial equator; half of the ecliptic lies north of the equator while the other half lies to the south. The north-south motion of the sun is the cause of the seasonal variations in the temperatures of the two hemispheres. The *year of the seasons* is defined therefore as the time that elapses from the moment the sun crosses the celestial equator in March until it passes around the ecliptic and crosses the celestial equator again in the same direction, i.e., from south to north.

To sum up, *the total motion of the sun relative to the earth is most conveniently described by saying that it is compounded of a slow annual motion along the ecliptic and the rapid diurnal motion of the celestial sphere itself relative to the earth.*

6.2. The sequence of diagrams in Fig. 1–6 will help to clarify this analysis of the sun's motion. At this stage of the discussion we shift our point of view from the individual observer, whose private horizon plane is oriented in a manner depending on his geographical position on the earth's surface, and instead look at the whole earth in relation to the celestial sphere. It is now convenient to think of the center of the quasi-infinite celestial sphere as being situated at the center of the earth rather than at an observatory somewhere on its surface. On this basis the diagrams of Fig. 1–6 show a small spherical earth at the center of the celestial sphere. By this means we emphasize the essential identity of the axes and equatorial planes of the two spheres.

Diagram *a* shows the approximately circular path of the sun as it moves around the earth once each day with the celestial sphere. But the sun does not follow exactly the same path through the sky each day as do the stars. In the spring it spirals northward (Diagram *b*) and in the fall it spirals southward. Over the year the coils of its track fill a band on the celestial sphere that extends $23\frac{1}{2}°$ on either side of the celestial equator.

The simpler path of the sun relative to the stars (i.e., the *ecliptic*) is depicted in Diagram *c*, where it is seen as a great circle oblique to the celestial equator. The motion of the sun on the ecliptic carries it around the polar axis in a sense *opposite* to that of the daily

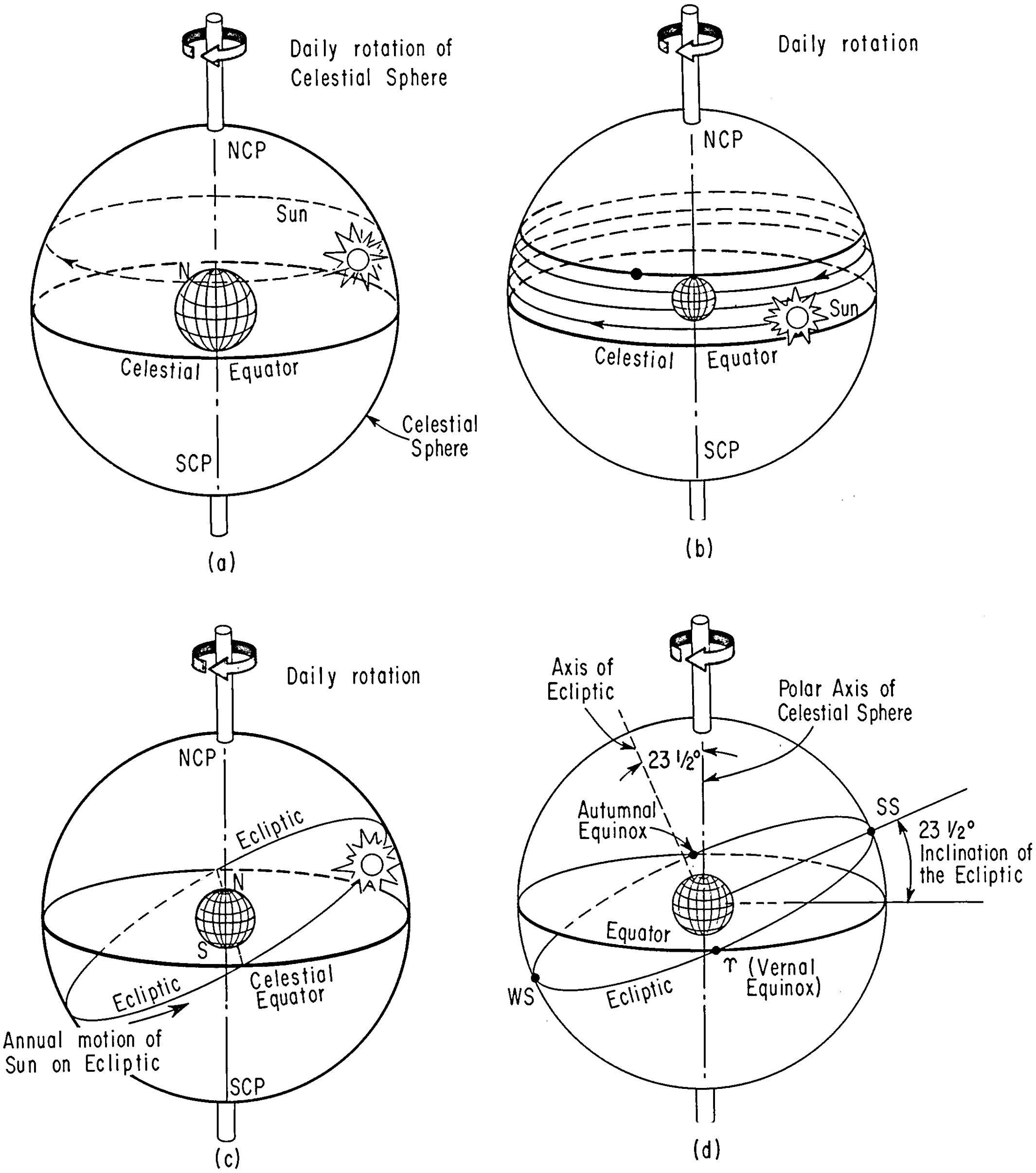


Fig. 1–6. *The Daily and Annual Motions of the Sun.*

Diagram *a.* Daily rotation of the sun about the earth.

Diagram *b.* Unlike the stars, the sun spirals northward in the spring and southward in the autumn.

Diagram *c.* Superposed on the daily rotation is a slow annual motion around the ecliptic circle. It is the combination of the daily rotation and the motion along the ecliptic that produces the spirals of Diagram *b.*

Diagram *d.* The inclination of the ecliptic is the angle of 23½° between the plane of the ecliptic and that of the celestial equator. The *vernal equinox* ♈ and the *autumnal equinox* are the two points at which the ecliptic crosses the celestial equator in the spring and autumn, respectively. The *summer solstice* (SS) and the *winter solstice* (WS) are the points of the sun's maximum distance from the equator.

rotation of the stars. Relative to the earth the sun falls behind the stars each day or, what amounts to the same thing, the stars gain on the sun. In a year of about 365 days the stars gain one complete revolution (360°). Thus the stars advance about 1° per day and 30° per month relative to the sun.

The *inclination,* or *obliquity, of the ecliptic* is the angle of about $23\frac{1}{2}°$ between the plane of the ecliptic and the plane of the celestial equator (Diagram *d*). It is equal to the angle between the *axis of the ecliptic* shown in the diagram and the polar axis of the celestial sphere. It is also identical with the angle between the equatorial line and the line of the ecliptic at both points where these lines cross.

It will be evident from Diagram *d* that the maximum northerly angular displacement of the sun from the celestial equator in summer is equal to the inclination of the ecliptic. The maximum southerly angular displacement in winter has the same value. Hence, the total angular displacement of the sun in the north and south direction between the extreme positions in winter and summer is double the inclination of the ecliptic.

7. The Seasons

7.1. The seasonal changes caused by the annual north-and-south migration of the sun relative to the earth depend markedly on the geographic latitude. Near the poles the celestial equator is close to the horizon and the diurnal circles are inclined at small angles to the horizon. Hence, the northward movement of the sun in summer produces diurnal circles (daily sun tracks) near the north pole that do not cut below the horizon at night — thus giving rise to a midnight sun. But in winter there is a long period in which the sun's diurnal circles lie wholly beneath the horizon — the time of the "long night." Thus the alternation of the seasons tends in the polar regions to be an alternation from 24-hour daylight to 24-hour darkness.

The situation is quite different in the tropics, where the celestial equator crosses the meridian close to the zenith. Although the December sun passes south of the zenith and the June sun north of the zenith, it is nearly overhead at both times, and the effect of the migration on the length of the day and on the mean daily temperature is minimized.

7.2. These effects are interesting, but for simplicity we direct our chief attention to the seasonal consequences of the sun's migration as they are observed in the north temperate zone. Figure 1–7 will serve to illustrate the annual changes in the sun's track in the sky as observed at the latitude of New Orleans (30° north). *In the rest of this discussion it is assumed, in the absence of an explicit statement to the contrary, that the observer is in the north temperate zone;* Fig. 1–7 is applicable in a qualitative sense.

On or about March 21 and again on or about September 22 the sun crosses the celestial equator. On these dates the sun's diurnal circle follows the celestial equator and is bisected by the horizon plane (cf. Fig. 1–6*c*). Hence, the length of the day from sunrise to sunset is everywhere equal to the length of the night.

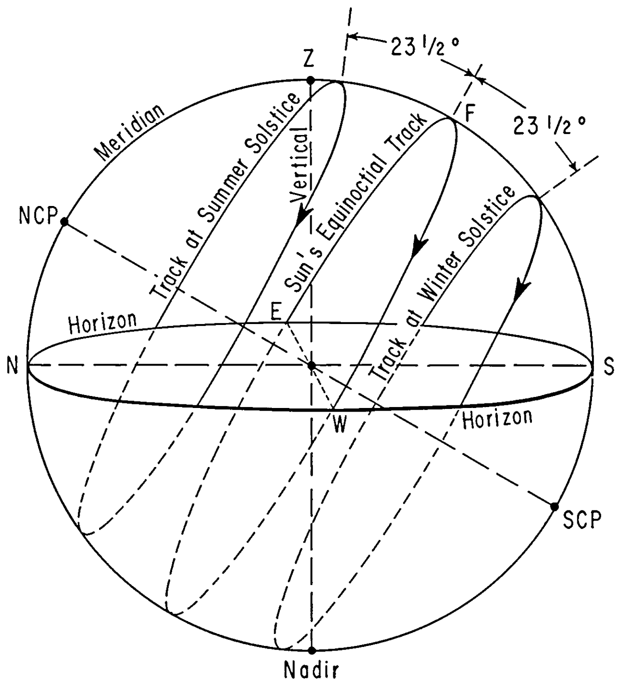


Fig. 1–7. *Tracks of the Sun at the Solstices and the Equinoxes.* At the equinoxes the sun's diurnal circle follows the celestial equator and is bisected by the horizon plane. At the summer solstice, however, the sun's diurnal circle, being 23½° north of the celestial equator, rises and sets well to the north of the east-west line. To the observer in the north temperate zone much more than half the diurnal circle is above the horizon plane. Conversely, at the winter solstice the sun is 23½° south of the celestial equator. Hence, much less than half of the sun's diurnal circle lies above the horizon plane for an observer in the north temperate zone. The length of the day from sunrise to sunset goes up and down with the fraction of the diurnal circle above the horizon.

From this equality of day and night these dates and the corresponding points on the celestial sphere where the ecliptic crosses the celestial equator are known as the *vernal equinox* and the *autumnal equinox*, respectively. At the equinoxes the sun at noon by apparent solar time (cf. Chap. 2, Sec. 7.5) for observers at the earth's equator is directly overhead. The sun rises and sets on the east-west line at all latitudes.

On or about June 21 the sun reaches the most northerly point of the ecliptic. This point and the date at which it is passed are designated as the *summer solstice*. On this date the sun's track in the sky (i.e., its diurnal circle) is about 23½° north of the celestial equator, as shown in the figure. In the north temperate zone the sun is higher at noon on the day of the summer solstice than at any other time of year. The sun rises and sets well to the north of the east-west line, and the fraction of its diurnal circle above the horizon reaches its annual maximum. The length of the day from sunrise to sunset is also a maximum.

On the day of the summer solstice the noonday shadow of a vertical shaft or pole has a minimum length for points north of the tropics. The rays of sunlight (Fig. 1–8) are more nearly perpendicular to the level surface of the earth than at any other time of the year and so deliver on the average more heat per hour of daylight than at other times. This fact combines with the added daylight to maximize the heat supplied per day and bring on the higher mean daily temperatures of summer.

On or about December 21, when the sun is farthest south, we have the *winter solstice.* This is the "shortest day" in the year, i.e., the day of minimum daylight, and the time at which the daily intake of heat from the sun is least.

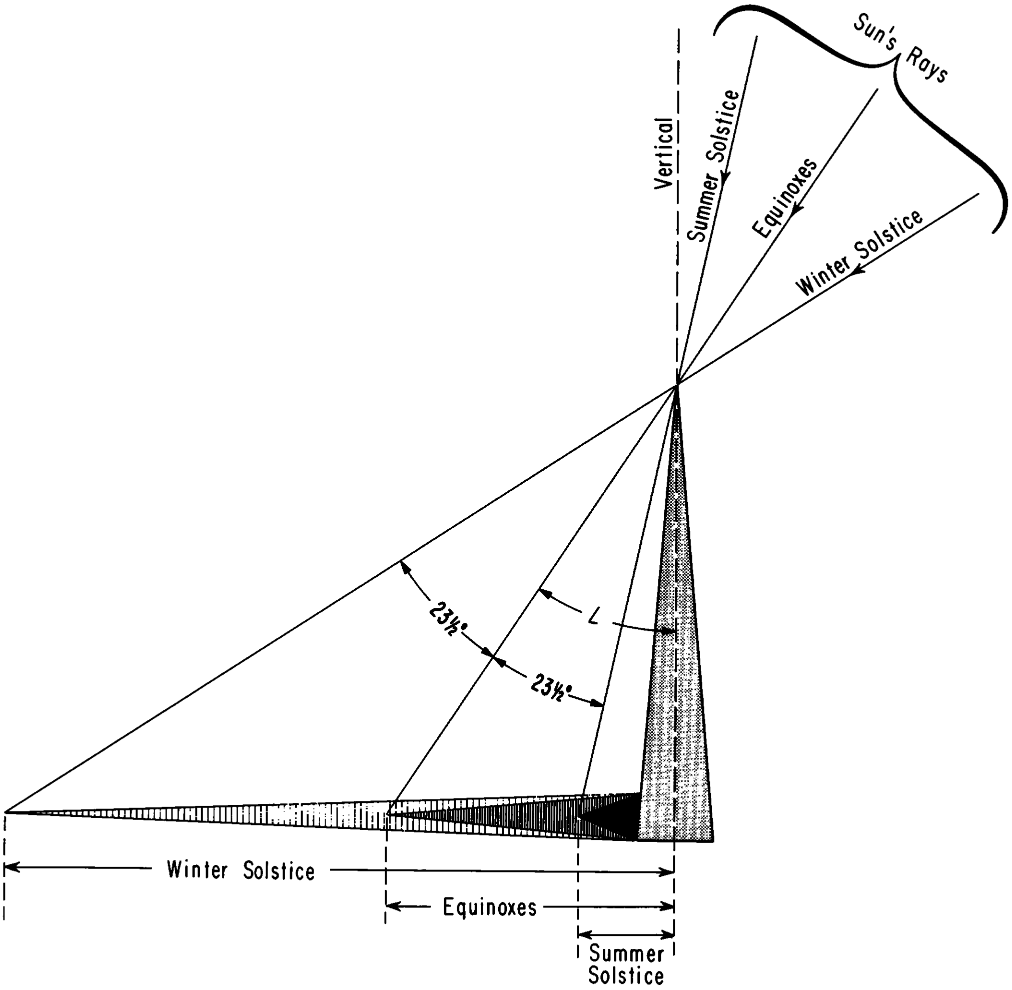


Fig. 1-8. *Seasonal Changes in Noon Shadows Cast by a Needle-Shaped Vertical Pointer.* The angle *L* between the vertical and the direction of the sun's rays at the equinoxes is equal to the geographic latitude.

The summer season and winter season lag behind the corresponding solstices because it takes time for the earth's surface temperature to warm up and cool down in response to increases and decreases in the mean daily intake of heat from the sun.

7.3. Since the day is fixed by the motion of the sun, which lags behind the stars in their rotation by about 30° each month, the stars opposite the sun, and consequently near the meridian at midnight, shift with the seasons.

The *zodiacal belt*, or "zone of animals," is an imaginary band on the celestial sphere first conceived by the Babylonians of the fifth century B.C. The belt borders the ecliptic and is about 16° wide. This width is sufficient to include the paths of the moon and the five bright planets known to the ancients, for these bodies never move far from the plane of the ecliptic. The *zodiacal constellations* are 12 groups of stars, many of them named for animals, that succeed one another at about 30° intervals as we look around the belt. Associated with these constellations are 12 segments of the belt, each 30° long, called the *signs of the zodiac*. During the year the sun passes from sign to sign and obscures the zodiacal constellations one after another at monthly intervals. This relationship explains the appearance of the picturesque symbols for the signs of the zodiac on old almanacs.

The names of the signs, Aries, Taurus, Gemini, Cancer, and so on, are usually listed in the order in which the sun passes through them after the vernal equinox, the natural starting point of the seasonal year. The vernal equinox fixes the west boundary of the sign of Aries; hence, the sun enters the sign of Aries when it crosses the celestial equator in March. The vernal equinox is often called the *first of Aries* and is symbolized by the "ram's horn" symbol ♈ of the sign Aries.

Originally (i.e., 2000 years ago) each zodiacal constellation was located in the corresponding sign, but to the confusion of the beginner this is no longer so. The equinoctial points are subject to an exceedingly slow westward drift relative to the stars, which we call the *precession of the equinoxes* (cf. Sec. 9). Since the signs of the zodiac are tied, as matter of convenience, to the equinoxes, the zodiacal constellations shift slowly eastward relative to the signs. The displacement that has occurred amounts in all to about 30°, the length of one segment of the belt. Thus each constellation is now located in the next succeeding sign after the one to which it was originally assigned. The constellation of Aries is in the sign of Taurus, the constellation of Taurus is in the sign of Gemini, and so on.

Each zodiacal constellation is overhead at midnight six months after the sun has passed the center of that constellation and seven months after it has passed the center of the corresponding sign.

The sun enters the sign of Cancer at the summer solstice when it reaches the angle of $23\frac{1}{2}°$ north of the celestial equator. The *tropic of Cancer* is a circle on the earth's surface, $23\frac{1}{2}°$ north of the equator, at which the sun is directly overhead at noon on the summer solstice. The *tropic of Capricorn* is a similar circle, $23\frac{1}{2}°$ south of the equator, at which the sun is directly overhead when it enters the sign of Capricorn at the winter solstice. At points between the two tropics the sun in its annual migration passes from the north side of the zenith to the south and back.

8. Measuring the Length of the Year

8.1. After counting, one of the first great practical problems that required a scientific solution was how to measure time. The ancients had no need of high precision in measuring small intervals. Accurate watches are necessary for maintaining railway or plane schedules and for other synchronized activity but have no place in a primitive agricultural economy. Even before the dawn of civilization, however, there was need for some method of keeping track of the seasons of the year more accurately than simply by observing the state of the vegetation. It was important to know how soon the monsoons would come, when the Nile would be flooded, how soon one might safely plant one's crops, how soon the birds and fishes would begin to migrate.

The answer to this need came through the observation of the heavens. Savage tribes far from city lights are of course more familiar with the stars than we are, and even the most primitive peoples are aware of a relation between the star groups appearing in the night sky, the sun's height at noon, and the seasons. There are in fact two sorts of astronomical phenomena that pass through a regular annual cycle: the shifting of the constellations overhead from night to night through the year, and the seasonal north-and-south motion of the midday sun with its attendant lengthening and shortening of midday shadows. Both have been used since the dawn of history to fix the seasons and determine the length of the year.

A primitive animistic view of nature linked the annual astronomical and seasonal cycle with the will of gods who needed propitiation. Religious ritual was developed to mark particular points in the cycle, and the business of observing the stars became a function of the priesthood. Thus, the first scientific observations of astronomy were wrapped in magical rites and became the sole possession of the initiated members of a particular social class.[9] The association of this branch of science with notions now regarded as superstitious has persisted to the present day in the form of astrology.

8.2. In the making of their calendars, the ancients had to wrestle with three natural time units whose relations to each other are not simple. These are the day, the lunar month, and the year — each defined by an impressive natural cyclic process affecting daily life. Of these three the lunar month, the time between successive full moons, has been pretty much discarded. The 12 months of the modern year are arbitrary intervals of time that are roughly equal in length to the cycle of the moon's phases, but no attempt is made to measure long intervals of time in terms of the lunar cycle. The day and the astronomical year are the units we use today, our system of leap years being a practical scheme for dealing with the unfortunate fact that the number of days in a natural astronomical year is not an integer but a fraction.

8.3. The evaluation of the length of the natural year in days and hours was one of the first important scientific achievements of ancient man. This evaluation can be done by careful and systematic observation of the cyclic variation in the length of a noonday shadow (cf. Fig. 1–8), by observation of the north-south oscillation of sunrise and sunset points, or by measuring the variations in the length of the day from sunrise to sunset. It suffices in any of these methods to count the days from the time that the variable under observation, such as the sunrise point used at Stonehenge, passes through a particular value until it passes through the same value again in the same direction a year later. If the counting is extended

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[9] The archaeologist V. Gordon Childe, speaking of those discoveries of the neolithic barbarians having to do with the chemistry of the potter's art, the biochemistry of baking and brewing, agricultural botany, and the like, says, "The practical technical prescriptions of barbarian science were, for sure, inextricably entangled with a mass of futile spells and rituals. Even the intelligent and highly civilized Greeks still feared a demon who used to crack the pots while they were being fired, so they affixed a hideous Gorgon mask to the kiln to scare him away!" See V. Gordon Childe, *What Happened in History* (Penguin Books, Ltd., Harmondsworth, England, 1942), p. 63.

over many years, division of the whole number of days by the number of years, say N, gives a value for the length of one year that is accurate to an Nth part of a day.

Another method is to observe the point when the sun in its annual journey around the ecliptic passes a particular bright star. Just before this happens, the star is an evening star, seen for a brief period dropping toward the western horizon in the afterglow of sunset. Just afterward the star is a morning star that appears briefly above the eastern horizon before the sunrise blots it out. We cannot directly observe the time when the sun passes the star, but we can determine it indirectly from measurements of the angle between the star and the sun at intervals before and after one passes the other.

8.4. The ancient Egyptians actually based their year on observations of the times at which the sun passes Sirius, the brightest star in the sky. By 4000 B.C. their priests had fixed the length of the year as 365 days. By 2000 B.C. they had observations to show that the 365-day year was 6 hours too short. We now use an extra day every leap year to compensate for the 6 hours.

The difficulties ancient peoples met in attempting to adjust their calendars to the fractional relationships of the day, the lunar month, and the year make a fascinating story that lies outside the scope of this volume.[10] Suffice it to say that modern precision measurements fix the length of the seasonal, or tropical year as 365.24220 days, or 365 days, 5 hours, 48 minutes, and 46.0 seconds. Our present calendar was established by Pope Gregory XIII in 1582. It creates legal years of exactly 365 or 366 days, so distributed over the centuries that their average length approximates the measured length of the seasonal year. The mean Gregorian year is actually 26 seconds longer than the seasonal year; a discrepancy of one day will accumulate in about 3300 years. We will return to the problem of measuring time in Chap. 2, Sec. 7.

9. The Precession of the Equinoxes

9.1. Records of the position of stars on the celestial sphere were made as early as 300 B.C. by Arstillus and Timocharus, Greek astronomers of the famous Alexandrian school (cf. Chap. 3, Sec. 3). About 150 years later Hipparchus, in some respects the greatest of the Greek astronomers, compared these records with his own careful observations and found systematic discrepancies. The discrepancies showed that in the course of 150 years the equinoctial points had moved about 2° westward along the ecliptic. There had occurred, in other words, a gradual shift of the celestial equator and the associated axis of celestial rotation relative to the stars.

The phenomenon discovered by Hipparchus is called the *precession of the equinoxes*, because the equinoxes seem to step forward ahead of the stars to meet the sun. The existence of the phenomenon means that the motion of the celestial sphere relative to the earth is not quite the simple rotation about a fixed axis

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[10] See L. Hogben, *Science for the Citizen* (W. W. Norton and Co., Inc., New York, 1938), pp. 47ff.; *The Legacy of Egypt*, edited by S. R. K. Glanville (Clarendon Press, Oxford, 1942), Chap. 1.

that we have hitherto assumed. It is more like the motion of a top, which, when properly started, spins about its axis of symmetry while that axis in turn slowly revolves about the vertical.

9.2. In describing the precession phenomenon it is convenient to introduce the *axis of the ecliptic* (Fig. 1–9), defined as that diameter of the celestial sphere which is perpendicular to the plane of the ecliptic. The points at which the axis of the ecliptic pierces the celestial sphere are called the *poles of the ecliptic.* The northern pole of the ecliptic is shown on the star map of Fig. 2–14 in the constellation of Draco, $23\frac{1}{2}°$ from the north celestial pole.

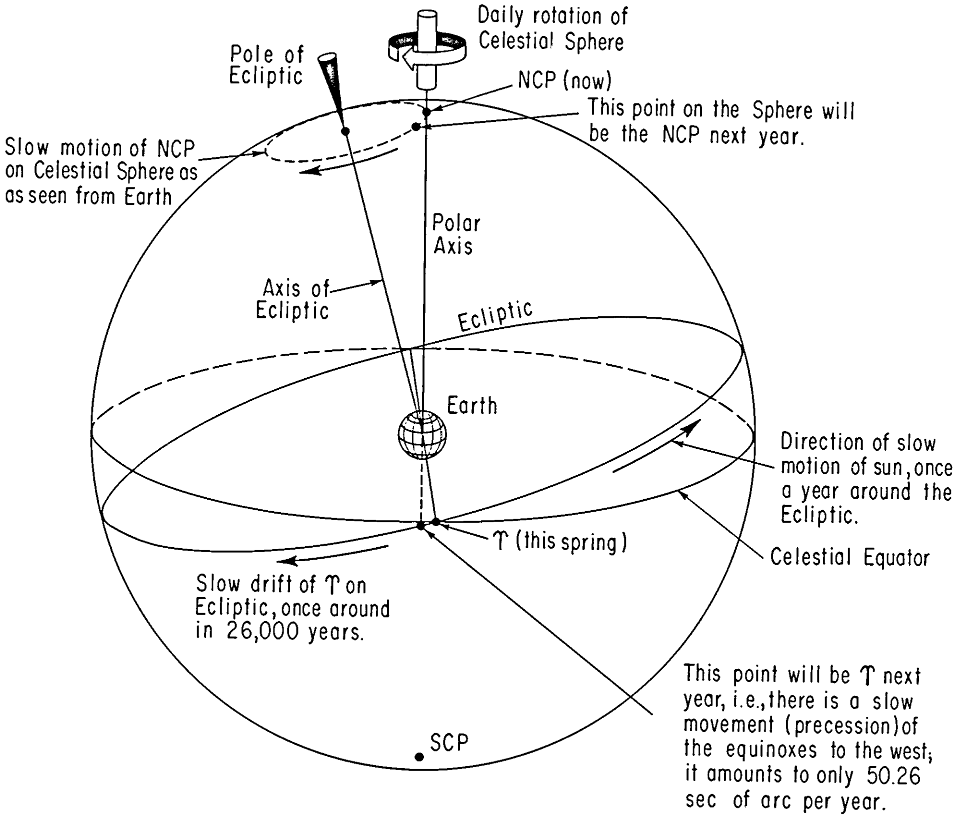

Fig. 1–9. *The Precession of the Equinoxes (geocentric description).* This figure shows a "snapshot" of the celestial sphere with the ecliptic and its axis, the momentary position of the celestial equator and its axis. The ecliptic and its axis are fixed relative to the stars, but in 26,000 years the north celestial pole rotates as indicated about the pole of ecliptic, carrying the polar axis and the equator with it. In its annual march around the ecliptic, the sun re-encounters the intersection of the ecliptic with the equator, namely, ♈, before 360° have been quite completed, because the celestial equator moves with the north celestial pole. Thus the sun's travel from ♈ to ♈ in the tropical year is 20 minutes shorter than from a fixed point on the ecliptic around the circle to the same point.

Careful modern studies show that the axis of celestial rotation and the axis of the ecliptic are both in motion relative to the stars, but the latter motion is relatively small; for our purpose it can be ignored. In first approximation, then, we can regard the ecliptic, its axis and poles, as fixed with respect to the celestial sphere. On the other hand, the north celestial pole, which forms for us the "visible" end of the axis of diurnal rotation of the celestial sphere, moves very slowly around the nearby pole of the ecliptic along a nearly circular path whose radius is fixed by the angle of $23\frac{1}{2}°$ between the two axes (the *obliquity of the ecliptic*). The motion, which carries the celestial equator with it, is shown in Fig. 1–9. The period of this precessional rotation, worked out from the observed displacement of the equinoxes over the last 2000 years, is 26,000 years. It follows that the shift of the celestial pole in a single year is exceedingly small, although the total displacement since the first astronomical observations has been large. The resulting westward motion of the equinoctial points amounts to 50.26 seconds of arc per year. According to Dreyer[11] the value worked out by Hipparchus must have been 45 or 46 seconds a year.

9.3. Because of the precession of the equinoxes, the stars in the sky now occupy positions relative to the celestial poles and the celestial equator quite different from those they occupied 5000 years ago. The Pole Star in the year 3000 B.C. was α Draconis, now 25° away from the pole. For much of the time between that date and the present there was no prominent star close to the Pole. Furthermore, the points at which the various stars rise and set have also shifted through the centuries.

A further consequence of the precession of the equinoxes is that the seasonal, or *tropical*, year defined as the interval between one vernal equinox and the next, is different from the time required for the sun to make one complete revolution on the ecliptic with respect to the stars. This latter interval of time is called the *sidereal* year. In the modern heliocentric theory it is the time for the earth to make one complete revolution in its orbit around the sun. Because of the displacement of the vernal equinox, the sidereal year is 20 minutes longer than the tropical year. The Egyptians, in dating their year by the time when the sun passes Sirius, were measuring the sidereal year rather than the tropical year.

Exercises

Exercise 1–1: Work out a detailed plan for measuring the length of the year by noonday shadows. How could you minimize the uncertainty due to the fuzziness of shadows cast by the sun? Would you achieve greater accuracy by making observations near one of the equinoxes, or near the summer solstice? Would it help very much to use a long pointer to cast shadows?

Exercise 1–2: Work out and describe in detail a plan for measuring the length of the year by observation of the times at which the sun passes a bright star. Assume that you are in possession of a clock or watch and some kind of instrument for measuring the altitude of sun or star above the horizon.

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[11] J. L. E. Dreyer, *History of the Planetary Systems from Thales to Kepler* (Cambridge University Press, Cambridge, 1905), Chap. 9. This book is now available as a Dover reprint under the title, *A History of Astronomy from Thales to Kepler*, 1953.