THE COPERNICAN REVOLUTION

Planetary Astronomy in the Development of Western Thought

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PREFACE

The story of the Copernican Revolution has been told many times before, but never, to my knowledge, with quite the scope and object aimed at here. Though the Revolution’s name is singular, the event was plural. Its core was a transformation of mathematical astronomy, but it embraced conceptual changes in cosmology, physics, philosophy, and religion as well. These individual aspects of the Revolution have been examined repeatedly, and without the resulting studies this book could not have been written. The Revolution’s plurality transcends the competence of the individual scholar working from primary sources. But both specialized studies and the elementary works patterned on them necessarily miss one of the Revolution’s most essential and fascinating characteristics—a characteristic which arises from the Revolution’s plurality itself.

Because of its plurality, the Copernican Revolution offers an ideal opportunity to discover how and with what effect the concepts of many different fields are woven into a single fabric of thought. Copernicus himself was a specialist, a mathematical astronomer concerned to correct the esoteric techniques used in computing tables of planetary position. But the direction of his research was often determined by developments quite foreign to astronomy. Among these were medieval changes in the analysis of falling stones, the Renaissance revival of an ancient mystical philosophy which saw the sun as the image of God, and the Atlantic voyages which widened the terrestrial horizons of Renaissance man. Even stronger filiations between distinct fields of thought appear in the period after the publication of Copernicus’ work. Though his De Revolutionibus consists principally of mathematical formulas, tables, and diagrams, it could only be assimilated by men able to create a new physics, a new conception of space, and a new idea of man’s relation to God. Creative interdisciplinary ties like these play many and varied roles in the Copernican Revolution. Specialized accounts are inhibited both by aim and method from examining the nature of these ties and their effects upon the growth of human knowledge.

This account of the Copernican Revolution therefore aims to dis-
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play the significance of the Revolution's plurality, and that object is probably the book's most important novelty. Pursuit of the object has, however, necessitated a second innovation. This book repeatedly violates the institutionalized boundaries which separate the audience for "science" from the audience for "history" or "philosophy." Occasionally it may seem to be two books, one dealing with science, the other with intellectual history.

The combination of science and intellectual history is, however, essential in approaching the plural structure of the Copernican Revolution. The Revolution centered in astronomy. Neither its nature, its timing, nor its causes can be understood without a firm grasp upon the data and concepts that were the tools of planetary astronomers. Astronomical observations and theories therefore make up the essential "scientific" component which dominates my first two chapters and recurs throughout the remainder of this book. They do not, however, make up the whole book. Planetary astronomy was never a totally independent pursuit with its own immutable standards of accuracy, adequacy, and proof. Astronomers were trained in other sciences as well, and they were committed to various philosophical and religious systems. Many of their nonastronomical beliefs were fundamental first in postponing and then in shaping the Copernican Revolution. These nonastronomical beliefs compose my "intellectual history" component, which, after Chapter 2, parallels the scientific. Given the purpose of this book, the two are equally fundamental.

Besides, I am not convinced that the two components are really distinct. Except in occasional monographs the combination of science and intellectual history is an unusual one. Initially it may therefore seem incongruous. But there can be no intrinsic incongruity. Scientific concepts are ideas, and as such they are the subject of intellectual history. They have seldom been treated that way, but only because few historians have had the technical training to deal with scientific source materials. I am myself quite certain that the techniques developed by historians of ideas can produce a kind of understanding that science will receive in no other way. Though no elementary book can fully document that thesis, this one should provide at least preliminary evidence.

Indeed it has already provided some evidence. The book grows out of a series of lectures delivered each year since 1949 in one of the science General Education courses at Harvard College, and in that application the combination of technical and intellectual-historical materials has been quite successful. Since students in this General Education course do not intend to continue the study of science, the technical facts and theories that they learn function principally as paradigms rather than as intrinsically useful bits of information. Furthermore, though the technical scientific materials are essential, they scarcely begin to function until placed in a historical or philosophical framework where they illuminate the way in which science develops, the nature of science's authority, and the manner in which science affects human life. Once placed in that framework, however, the Copernican system or any other scientific theory has relevance and appeal for an audience far broader than either the scientific or the undergraduate community. Though my first purpose in writing it was to supply reading for the Harvard course and for others like it, this book, which is not a text, is also addressed to the general reader.

Many friends and colleagues, by their advice and criticism, have helped to shape this book, but none has left so large or significant a mark as Ambassador James B. Conant. Work with him first persuaded me that historical study could yield a new sort of understanding of the structure and function of scientific research. Without my own Copernican revolution, which he fathered, neither this book nor my other essays in the history of science would have been written.

Mr. Conant also read the manuscript, and its early chapters show many signs of his productive criticisms. Others who will recognize here and there the effects of their useful suggestions include Marie Boas, I. B. Cohen, M. P. Gilmore, Roger Hahn, G. J. Holton, E. C. Kemble, P. E. LeCorbeiller, L. K. Nash, and F. G. Watson. Each has applied critical talent to at least one chapter; several read the entire manuscript in an earlier version; and all have rescued me from mistakes or ambiguities. The advice of Mason Hammond and Mortimer Chambers has given my occasional Latin translations an assurance that they would not otherwise possess. Arnoldo Ferruolo first introduced me to Ficino's De Sole and showed me that Copernicus' attitude toward the sun is an integral part of a Renaissance tradition more striking even in the arts and literature than in the sciences.

The illustrations display the skill, but scarcely the patience, with which Miss Polly Horan has translated and retranslated my vague
directions into communicative symbols. J. D. Elder and the staff of the Harvard University Press have given me constant and sympathetic guidance in the arduous transmutation to type of a manuscript that conforms neither to the rules for scientific publication nor to those for history. The index attests the industry and intelligence of W. J. Charles.

The joint generosity of Harvard University and the John Simon Guggenheim Memorial Foundation provided the year's leave of absence during which most of my manuscript was first prepared. I am also grateful to the University of California for a small grant which assisted in the final preparation of the manuscript and in seeing it through the press.

My wife has been an active participant throughout the book's development, but that participation is the least of her contributions to it. Brain children, particularly someone else's, are the most obstreperous members of any household. Without her continuing toleration and forbearance this one would never have survived.

T. S. K.

Berkeley, California
November 1956

Note to the Seventh Printing. This printing contains a number of corrections and textual changes inadvertently omitted from earlier Harvard editions. With this and subsequent printings, all changes previously introduced in the Random House and Vintage paperback editions are also included in the Harvard Paperback together with a few minor corrections after the earlier paperback editions were prepared.
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-
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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

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

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

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THE PROBLEM
OF THE PLANETS

Apparent Planetary Motion

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

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

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

The moon travels around the ecliptic faster and less steadily than the sun. On the average it completes one journey through the zodiac in 27.5 days, but the time required for any single journey may differ from the average by as much as 7 hours. In addition, the appearance of the moon's disk changes markedly as it moves. At new moon its disk is completely invisible or very dim; then a thin bright crescent appears, which gradually waxes until, about a week after new moon, a semicircular sector is visible. About 2 weeks after new moon the full circular disk appears; then the cycle of phases is reversed, and the moon gradually wanes, reaching new moon again about 1 month after the preceding new moon. The cycle of phases is recurrent, like the moon's journey through the signs of the zodiac, but the two lunar cycles are significantly out of step. New moon recurs after an average interval of 29.5 days (individual cycles may differ by as much as ½ day from this average), and, since this is 2 days longer than the period of an average journey around the zodiac, the position of successive new moons must gradually move eastward through the constellations. If new moon occurs at the position of the vernal equinox one month, the moon will still be waning when it returns to the vernal equinox 27.5 days later. New moon does not recur for about 2 days more, by which time the moon has moved almost 30° east from the equinox.

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

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

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

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

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

In their gradual eastward motions interrupted by periodic westward retrogressions, the five wandering stars behave quite similarly. But there is an additional characteristic of their motion which divides them into two groups; this is the correlation between their position and the sun's. Mercury and Venus, the two so-called inferior planets, never get very far from the sun. Mercury is always found within 28° of the sun's moving disk, and Venus's maximum "elongation" is 45°. Both planets move in a continuous slow shuttle, back and forth across the moving sun; for a time they move eastward with the sun, then retrogress across its disk, and finally reverse themselves to overtake the sun once more. When to the east of the sun, either of these inferior planets appears as an "evening star," becoming visible shortly after sunset and then rapidly following the sun below the horizon. After retrogressing westward across the sun's disk, the planet becomes a "morning star," rising shortly before dawn and disappearing in the brilliant light of sunrise. But in between, when close to the sun, neither Mercury nor Venus can be seen at all. Therefore, until their motion was analyzed with respect to the sphere of the stars, neither of the inferior planets was recognized as the same celestial body when it appeared as a morning and as an evening star. For millenniums Venus had one name when it rose in the east shortly before dawn and another when, weeks later, it again became visible just over the western horizon shortly after sunset.

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

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

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

The Location of the Planets

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

THE PROBLEM OF THE PLANETS

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

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

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

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

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

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

![Figure 16. Approximate planetary orbits in the two-sphere universe. The outermost circle is a cross section of the stellar sphere in the plane of the ecliptic.](image)

To this point the order is unambiguous: the planets are arranged, from the outside, in the order of decreasing orbital period; the same technique places the lunar orbit closest to the earth. But the remaining three planets present a problem; the sun, Venus, and Mercury all complete their journeys about the earth in the same average time, 1 year, and their order therefore cannot be determined by the device applied to the other planets. There was, in fact, much disagreement about their
COPERNICUS' INNOVATION

Copernicus and the Revolution

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

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

COPERNICUS' INNOVATION

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

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

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

### Motives for Innovation — Copernicus’ Preface

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

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

**TO THE MOST HOLY LORD, POPE PAUL III**

The Preface of Nicholas Copernicus to the Books of the Revolutions

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

Thinking therefore within myself that to ascribe movement to the Earth must indeed seem an absurd performance on my part to those who know that many centuries have consented to the establishment of the contrary judgment, namely that the Earth is placed immovably as the central point in the middle of the Universe, I hesitated long whether, on the one hand, I should give to the light these my Commentaries written to prove the Earth’s motion, or whether, on the other hand, it was better to follow the example of the Pythagoreans and others who were wont to impart their philosophic mysteries only to intimates and friends, and then not in writing but by word of mouth, as the letter of Lysis to Hipparchus witnesses. [This letter, which Copernicus had at one time intended to include in the *De Revolutionibus*, describes the Pythagorean and Neoplatonic injunction against revealing nature’s secrets to those who are not initiates of a mystical cult. Reference to it here exemplifies Copernicus’ participation in the Renaissance revival of Neoplatonism discussed in the last chapter.] In my judgment they did so not, as some would have it, through jealousy of sharing their doctrines, but as fearing lest these so noble and hardly won discoveries of the learned should be despised by such as either care not to study aught save for gain, or — if by the encouragement and example of others they are stimulated to philosophic liberal pursuits — yet by reason of the dullness of
work was leading. During the seventeenth century many other scientific and cosmological currents converged to modify and complete the cosmological framework that had directed their thought. The Copernicanism that the eighteenth, nineteenth, and twentieth centuries inherited is a Copernicanism rebuilt to suit the seventeenth-century conception of a Newtonian world machine. That final historic integration of Copernican astronomy into the complete and coherent universe envisaged by the seventeenth century is the subject of our final chapter, though we shall treat it only with the limited detail and fore-shortened perspective appropriate to an epilogue. In so far as the Copernican Revolution was a revolution merely in astronomical thought, its story ends here. What follows is a partial sketch of the larger revolution in science and cosmology—a revolution which began with Copernicus and through which the Copernican Revolution was at last completed.

THE NEW UNIVERSE

The New Scientific Perspective

Kepler and Galileo compiled impressive evidence for the earth’s status as a moving planet. The concept of elliptical orbits and the new data collected with telescopes were, however, only astronomical evidence for the planetary earth. They did not answer the non-astronomical evidence against it. While they remained unanswered, each of those arguments, whether physical, or cosmological, or religious, testified to an immense disparity between the concepts of technical astronomy and those employed in other sciences and in philosophy. The more difficult it became to doubt the astronomical innovation, the more urgent was the need for adjustments in other fields of thought. Until those adjustments were made, the Copernican Revolution was incomplete.

Most large-scale upheavals in scientific thought produce similar conceptual disparities. We are today, for example, in the late stages of a scientific revolution initiated by Planck, Einstein, and Bohr. Their new concepts and others upon which the contemporary revolution depends show close historical parallels to Copernicus’ concept of a planetary earth. Conceptions like Bohr’s atom and Einstein’s finite but unbounded space were introduced to solve pressing problems in a single scientific specialty. Those who accepted them did so initially because of the immense felt need in the field of their origin and in spite of their obvious conflict with common sense, physical intuition, and the basic concepts of other sciences. For a time they were used by the specialist even though, within the larger climate of scientific thought, they seemed incredible.

Continued use, however, makes even the strangest conception plausible, and once plausible the new conception gains a larger scientific function. It ceases, in the vocabulary of Chapter 1, to be merely a paradoxical and ad hoc device for economically describing the
known, and becomes instead a basic tool for explaining and exploring nature. At this stage the new conception cannot be restricted to a single scientific specialty. Nature ought not display incompatible properties in different fields. If the physicist's electron can leap from path to path without crossing the intervening space, then the chemist's electron should have the same ability, and the philosopher's concept of matter and space demand reexamination. Every fundamental innovation in a scientific specialty inevitably transforms neighboring sciences and, more slowly, the worlds of the philosopher and the educated layman.

Copernicus' innovation is no exception. In the early decades of the seventeenth century it was at best an astronomical innovation. Outside of astronomy it raised a host of problems just as perplexing and far more obvious than the questions of numerical detail it had resolved. Why do heavy bodies always fall toward the surface of a spinning earth as the earth moves in its orbit about the sun? How far away are the stars, and what is their role in the structure of the universe? What moves the planets, and how, in the absence of spheres, are they kept in their orbits? Copernican astronomy destroyed traditional answers to these questions, but it supplied no substitutes. A new physics and a new cosmology were required before astronomy could again participate plausibly in a unified pattern of thought.

Before the end of the seventeenth century that new science and cosmology had been created, and the men responsible were all members of the Copernican minority. Their adherence to Copernicanism gave a new shape and direction to much of their research. It provided a new set of problems, one of which — what moves the earth? — has already emerged briefly in our study of Kepler's *anima motrix*. In addition, Copernicanism supplied a multiplicity of hints about the concepts and techniques that the solution of these new problems demanded. By suggesting, for example, the unification of terrestrial and celestial laws, it made the projectile a legitimate source of information about planetary motions. Finally, Copernicanism gave a new meaning and value to a number of cosmological doctrines which, though current as minority views in antiquity and the Middle Ages, had previously been disregard by most scientists. During the seventeenth century several of these newly popular views, particularly atomism, were a constant source of significant suggestions for science.

**The New Universe**

These new problems, new techniques, and new evaluations constitute the new perspective that seventeenth-century science gained from Copernicanism. The last chapter displayed the effects of this new perspective upon astronomy. This one will show its role in the development of other sciences and of cosmology, for the Newtonian universe was born in an intellectual climate that Copernicanism had helped make fertile. But unlike Kepler's Laws, which are the astronomical culmination of the Copernican Revolution, the Newtonian universe is a product of more than Copernicus' innovation. In discussing its evolution and discovering how the concept of a planetary earth came at last to make coherent sense we shall therefore have occasionally to introduce concepts and techniques that have been neglected to this point because they had little bearing upon the development of astronomy or cosmology until after Copernicus' death. Our problem now becomes larger than the Copernican Revolution proper.

**Toward an Infinite Universe**

The Aristotelian universe had been, in most versions, a finite universe — matter and space ended together at the sphere of the stars — and most early Copernicans preserved this traditional feature. In the cosmologies of Copernicus, Kepler, and Galileo the center of the sun coincided with the center of the finite stellar sphere; the sun simply changed places with the earth, becoming the unique central body, the Neoplatonic symbol of the Deity. This new two-sphere universe was a natural revision of traditional cosmology. Since there was no concrete counterevidence, it might well have endured until the nineteenth century when improved telescopes showed that different stars were at very different distances from the sun.

The role of the two-sphere construction was, however, very different in the Aristotelian and Copernican world views; finitude, in particular, had essential functions in the first that were completely absent in the second. For example, in Aristotelian science the stellar sphere was needed to carry the stars in their diurnal circles and to provide the push that kept both the planets and terrestrial objects in motion. In addition, the outer sphere defined an absolute center of space, the center toward which all heavy objects moved of their own accord. Copernicus' universe deprived the sphere of all these functions and of others as well. Terrestrial motion did not demand an absolute
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center of space; stones fell toward the moving earth. Nor was an outer sphere needed to produce celestial motions; whether or not located on a sphere, the stars were at rest. Copernicans were still at liberty to preserve the stellar sphere, but only tradition could supply a motive for doing so. The sphere could be abandoned without disrupting either Copernican physics or cosmology.

Copernicanism therefore allowed a new freedom to cosmological thought, and the result was a new speculative conception of the universe that would surely have horrified both Copernicus and Kepler. A century after Copernicus' death his two-sphere framework had been replaced by a universe in which the stars were scattered here and there through an infinite space. Each of these stars was a "sun," and many of them were thought to possess their own planetary systems. By 1700 the unique earth, which Copernicus had reduced to but one of six planets, had become little more than a speck of cosmic dust.

Though historians still know little about the way in which this new Copernican conception was established, its origin is quite clear. By doing away with the cosmological functions of the outer sphere, Copernicus revitalized three earlier speculative conceptions of the universe, conceptions associated respectively with scholasticism, Neoplatonism, and atomism. Before the De Revolutionibus these three cosmologies were quite different in structure and motive, and none was relevant to celestial science. But all were transformed to scientific cosmologies by Copernicanism, and once transformed they showed remarkable structural similarities.

Consider first the most prevalent pre-Copernican conception of an infinite universe, developed by Islamic philosophers who could not accept Aristotle's proof of the logical impossibility of a void. This universe was substantially the same as Aristotle's from the central earth to the rotating stellar sphere, but beyond the sphere space no longer ceased to exist with matter. Instead, the entire Aristotelian universe was embedded as a kernel at the center of an infinite space devoid of matter, the abode of God and his angels. Because it did not constrain God's power to make an infinite universe, this conception became relatively popular in Europe after the thirteenth century. It was described in several well-known elementary books current during Copernicus' lifetime, and knowledge of the conception may have helped him to justify the expansion of the stellar sphere that was

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necessitated by the absence of observed parallax. But before Copernicus, this version of an infinite universe had had little bearing upon the practice of astronomy or any other science. So long as celestial bodies were conceived to be in continuous motion, they could not easily be placed in the infinite space beyond the outermost sphere. The functions of that space were theological, not physical or astronomical.

By bringing the stars to rest, however, Copernicus made it possible to give infinite space astronomical functions, and that new freedom was first exploited about a generation after the publication of the De Revolutionibus. In 1576 the English Copernican, Thomas Digges, introduced the idea of an infinite universe into an otherwise straightforward paraphrase of Copernicus' Book One, and the result, reproduced from Digges's original illustration, is shown in Figure 45. The central core of the universe is identical with the universe of the De Revolutionibus, but the stars have been removed from the surface of the stationary stellar sphere and scattered outward through the infinite space posited by the older minority cosmological tradition. Though few of Copernicus' immediate successors went as far as Digges, many of them recognized that the stars no longer had to be on a sphere and that the distances between individual stars and the sun might vary without affecting the appearances. When Galileo's telescope showed countless new stars where none had been seen before, the scattering of stars through an immeasurably distant space seemed to the less traditionally minded astronomers almost a matter of experience.

Digges was the first to describe an infinite Copernican universe, but he achieved infinity only by the unconscious introduction of a paradox which, in antiquity and the Middle Ages, had provided a principal reason for rejecting infinite space. Digges's unique central sun is a contradiction, for it is no more "at the center" than each one of the stars and planets. The center is the point that is equidistant from all points on the periphery, and that condition is satisfied by every point in an infinite universe or by none. This paradox had been fully elaborated a century before Copernicus by the important Neoplatonist, Nicholas of Cusa. He had believed that the universe was an infinite sphere—no smaller sphere would, he said, be consistent with God's creative omnipotence—and he had expressed the resulting para-
dox by declaring that the center of the sphere everywhere coincided with its periphery. In his universe each body, fixed or moving, was simultaneously at the center, on the surface, and in the interior. Be-

A perfect description of the Celestial Orbes,
according to the most ancient doctrine of the Pythagoreans, etc.

Figure 45. The infinite Copernican universe of Thomas Digges, reproduced from his Perfit Description of the Caelestial Orbes, published in 1576. The diagram is like all other early sketches of the Copernican universe except that the stars are no longer restricted to the surface of the celestial sphere. No stars occur within the sphere (if they did, there would be observable stellar parallax), but the infinite space beyond the sphere is studded with them. Notice, however, that the sun still retains a privileged position and that the distance between neighboring stars is far less than that between the sun and the celestial sphere. In Digges's universe the sun is not just another star.

cause no part of space could be distinguished from any other, the occupants of space—the earth, planets, and stars—must all move and must all be of the same nature.

Cusa’s vision provides a second example of a cosmology that could be transformed by the existence of Copernicanism. As Cusa developed it, a hundred years before the publication of the De Revolutionibus, the cosmology made no scientific sense at all. In the role of cosmologist, Cusa was a mystic who joyfully rejected the appearances for the sake of a transcendent apprehension of the infinite Deity in whom all paradoxes were reconciled. Yet the Neoplatonic insistence upon the infinite and its paradoxes was not intrinsically incompatible with the appearances or with science. After Copernicus’ death the same insistence provided a motive and recurrent theme for the cosmological writings of the Italian mystic, Giordano Bruno, and in Bruno’s vision of the universe the infinite and the appearances were reconciled by Copernicanism. Bruno’s approach to cosmology was scarcely more concerned with science or with the appearances than was the approach of Cusa, by whom he was greatly influenced. But whatever his motives Bruno was right. The sun need not be at the center; in fact, no center is needed. A Copernican solar system may be set down anywhere in an infinite universe. Providing only that the sun is far enough from the neighboring stars to account for the absence of parallax, the appearances will be preserved.

Bruno’s reconciliation of an infinite and centerless universe with the appearances was only one part of his cosmological construction. Beginning around 1584 he also made explicit the physical relation of the Copernican solar system to the other celestial residents of his infinite space. The sun was, he thought, merely one of an infinite number of stars scattered through the infinite expanse of space; some of the other bodies in the infinite heavens must be populated planets like the earth. Not only the earth but the sun and the entire solar system were transformed to insignificant specks lost in the infinitude of God’s creation; the compact and ordered cosmos of the scholastics had become a vast chaos; the Copernican departure from tradition had reached its maximum.

But though radical, this last extension of Copernicanism was achieved almost without novelty. Two millenniums before Bruno’s birth the ancient atomists, Leucippus and Democritus, had envisaged an
infinite universe containing many moving earths and many suns. In antiquity their doctrines had never rivaled Aristotle’s as a basis for scientific thought, and their writings had disappeared almost entirely during the Middle Ages. But the works of their successors, Epicurus and Lucretius, were among the principal literary recoveries made by the Renaissance humanists. From these works, particularly from Lucretius’ De Rerum Natura, Bruno derived many of his most fruitful conceptions. In Bruno’s cosmology a third ancient speculative conception of the universe was revitalized and given new verisimilitude by its affinity for Copernicanism.

That affinity is somewhat surprising, for both historically and logically atomism and Copernicanism seem totally different doctrines. The ancient atomists had developed the main tenets of their cosmology not principally from observation but in an attempt to resolve apparent logical paradoxes. The existence and motion of finite bodies could, they felt, be explained only if the real world consisted of tiny indivisible corpuscles, or atoms, swimming freely in a vast empty space, or void. The void was required to account for motion; if there were no empty spaces, there would be no place for matter to move into. Similarly, the indivisibility of the ultimate particles seemed to them essential for the existence of finite bodies; if matter were infinitely divisible, then its ultimate parts would be mere geometric points, occupying no space at all. From parts that, taken individually, occupy no volume it seemed impossible to construct a finite body that would. Zero plus zero equals zero no matter how often the addition is repeated. Reality must therefore, said the atomists, consist of indivisible atoms and the void, and this premise, quite foreign to Copernicanism, was the foundation of their world view.

The premise had, however, some striking consequences which were not so foreign. For example, the atomists’ void must be infinite in extent. It could only be bounded by matter, and the matter must, in turn, be bounded by more void. When matter and space ceased to go together, as they had in Aristotle’s physics, there was no end to the process of bounding the universe. Again, there were no special positions or unique bodies in the atomists’ universe. The void itself was neutral; each position was like every other. The earth or sun existed in one region rather than another simply because the fortuitous motions and collisions of the atoms happened to produce an aggregate at that position, and because once the atoms had met by chance they became entangled and stuck. The process could equally well have occurred somewhere else. In fact, since the universe was infinite and contained infinitely many atoms, the process almost certainly had occurred elsewhere at some time. Many earths and suns as well as many atoms populated the infinite void of atomistic cosmology. There was no possible terrestrial-celestial dichotomy. According to the atomists, the same sort of matter obeyed the same set of laws everywhere in the infinite neutral void.

Since Copernicanism also destroyed the earth’s uniqueness, abolished the terrestrial-celestial distinction, and suggested the infinity of the universe, the atomists’ infinite void provided a natural home for Copernicus’ solar system, or rather for many solar systems. Bruno’s principal contribution was recognizing and elaborating this obscure affinity between the ancient and modern doctrines. Once the affinity was recognized, atomism proved the most effective and far-reaching of the several intellectual currents which, during the seventeenth century, transformed the finite Copernican cosmos into an infinite and multipopulated universe. That extension of cosmological dimensions was, however, only the first of atomism’s significant roles in the construction of the new universe.

The Corpuscular Universe

Early in the seventeenth century atomism experienced an immense revival. Partly because of its significant congruence with Copernicanism and partly because it was the only developed cosmology available to replace the increasingly discredited scholastic world view, atomism was firmly merged with Copernicanism as a fundamental tenet of the “new philosophy” which directed the scientific imagination. Donne’s lament that because of the “new Philosophy” the universe was “crumbled out again to his Atomies” is an early symptom of the confluence of these previously distinct intellectual currents. By 1630 most of the men who dominated research in the physical sciences showed the merger’s effects. They believed that the earth was a moving planet, and they attacked the problems presented by this Copernican conception with a set of “corpuscular” premises derived from ancient atomism.

The “corpuscularism” that transformed seventeenth-century science
As a result the corpuscular philosophy was remade and the search for forces began. Near the beginning of the Principia Newton had said, I am induced by many reasons to suspect that ... [the phenomena of Nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards one another, and cohere in regular figures, or are repelled and recede from one another.4

And toward the end of his Opticks he added to a long series of “Queries” about the results of corpuscular action:

All these things being consider’d, it seems probable to me, that God in the Beginning form’d Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in such Proportion to Space, as most conduced to the End for which he form’d them. ... And therefore, that Nature may be lasting, the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of these permanent Particles. ... It seems to me farther, that these Particles have not only a Vis inertiae [inertial Force], accompanied with such passive Laws of Motion as naturally result from that Force, but also that they are moved by certain active Principles, such as is that of Gravity, and that which causes [chemical] Fermentation, and the Cohesion of Bodies.5

These statements and others like them describe the Newtonianism that played so large a role in the thought of the eighteenth and nineteenth centuries. After Newton’s death in 1727 most scientists and educated laymen conceived the universe to be an infinite neutral space inhabited by an infinite number of corpuscles whose motions were governed by a few passive laws like inertia and by a few active principles like gravity. From these premises Newton had deduced with unprecedented precision most of the known phenomena of optics and all the known phenomena of celestial and terrestrial mechanics, including both the tides and the precession of the equinoxes. Beginning where he had left off, his successors tried to discover the additional force laws required to account for the remaining natural phenomena: heat, electricity, magnetism, cohesion, and, above all, chemical combination. At last the crumbling Aristotelian universe was replaced by a comprehensive and coherent world-view, and a new chapter in man’s developing conception of nature was begun.

The New Fabric of Thought

The construction of Newton’s corpuscular world machine completes the conceptual revolution that Copernicus had initiated a century and a half earlier. Within this new universe the questions raised by Copernicus’ astronomical innovation were at last resolved, and Copernican astronomy became for the first time physically and cosmologically plausible. The earth’s relation to the other bodies in the universe was once again defined. Men again knew why a shot fired into space would return to the point from which it had departed, though they now understood that the shot must not be fired quite vertically. Only as Copernicanism became credible, through the dissemination and acceptance of this new conceptual framework, did the last significant opposition to the conception of a planetary earth disappear. Newton’s universe was not, however, merely a framework for Copernicus’ planetary earth. Far more important, it was a new way of looking at nature, man, and God—a new scientific and cosmologic perspective which, during the eighteenth and nineteenth centuries, repeatedly enriched the sciences and reshaped both religious and political philosophy.

The same Newtonian principles which, by providing an economical derivation and a plausible explanation of Kepler’s Laws, closed the astronomical revolution also supplied astronomy itself with a host of powerful new research techniques. For example, when improved quantitative techniques of telescopic observation showed that the planets do not really quite obey Kepler’s Laws, Newtonian physics made it possible first to explain and then to predict the planets’ minor deviations from their fundamental elliptical orbits. As Newton’s derivation had shown, Kepler’s Laws should apply rigorously only if the sun exerts the sole attractive force on each planet. But planets also attract each other, particularly when they approach and pass, and this extra attraction draws them out of their fundamental orbits and changes their speeds. During the eighteenth century mathematical extensions of Newton’s work enabled astronomers to predict these deviations with great precision, and during the nineteenth century the inversion of this predictive technique was responsible for one of astronomy’s greatest triumphs. In 1846 Leverrier in France and Adams in England independently predicted the existence and the orbit of a previously
unsuspected planet which they believed was the cause of unexplained irregularities in the orbit of the known planet Uranus. When the telescope was turned to the heavens, the new planet, Neptune, was discovered, dimly visible, within a degree of the position predicted by Newtonian theory.

Examples of Newtonianism's fruitfulness in astronomy could be multiplied almost endlessly, and astronomy was not the only science affected. To examine but one of the possible examples from one of many sciences, consider the impact of Newton's work upon chemical experimentation during the eighteenth century. In spite of his explicit intention Newton led most of his successors to believe that gravity, and therefore weight, were intrinsic properties of matter. He thus gave weight a new significance in science. It became, for the first time, an unequivocal measure of quantity of matter, and as a result the balance became a fundamental chemical instrument. The balance alone could tell the chemist how much matter was put into a chemical reaction and how much was evolved. Since antiquity chemists had believed that quantity of matter was conserved during chemical reactions, but there had been no widely accredited measure of "quantity of matter." In the climate of Aristotelian or even Cartesian thought weight was usually regarded, like color, texture, or hardness, as a secondary characteristic of matter — one that might be altered by the process of chemical reaction. The concept of weight as a universally accredited tool for "balancing" chemical reactions and for determining whether matter is lost to or gained from an unsuspected source during such reaction was therefore a partial product of Newtonianism. That new tool was one of the several important roots of the revolution in chemical thought that centered about the Frenchman Lavoisier during the last decades of the eighteenth century.

A whole book would be required to transform and multiply these two isolated examples — the discovery of Neptune and the new significance of weight — into a balanced discussion of the effects of the new universe upon science, and the discussion would still be incomplete. In the conceptual fabric that grew up around the new universe nonscientific thought was transformed as well. In the infinite and multipopulated universe conceived by seventeenth-century scientists and philosophers the localization of heaven in the skies and of hell beneath the earth's crust became mere metaphors, dying echoes of a symbolism that had once had concrete geographic significance. Simultaneously the conception of a universe constructed of atoms which move forever in accordance with a few God-given laws changed many men's image of the Deity Himself. In the clockwork universe God frequently appeared to be only the clockmaker, the Being who had shaped the atomic parts, established the laws of their motion, set them to work, and then left them to run themselves. Deism, an elaborated version of this view, was an important ingredient in late seventeenth- and eighteenth-century thought. As it advanced, the belief in miracles declined, for miracles were a suspension of mechanical law and a direct intervention by God and his angels in terrestrial affairs. By the end of the eighteenth century an increasing number of men, scientists and nonscientists alike, saw no need to posit the existence of God.

Other reflections of the new science can be discovered in the political philosophy of the eighteenth and nineteenth centuries. Several recent writers have pointed to the significant parallels between the seventeenth-century conception of a mechanically functioning solar system and the eighteenth-century conception of a smoothly running society. The system of checks and balances incorporated in the Constitution of the United States, for example, was intended to give the new American society the same sort of stability in the presence of disruptive forces that the exact compensation of inertial forces and gravitational attraction had given to the Newtonian solar system. Also, the eighteenth century's determination to derive the characteristics of a good society from the innate characteristics of the individual man may well have been fostered in part by the corpuscularism of the seventeenth century. In eighteenth- and nineteenth-century thought the individual appears again and again as the atom from which the mechanism, society, is fabricated. In the opening paragraphs of the Declaration of Independence, Jefferson derived the right to revolution from the God-given or inalienable rights of the social atom, man, and his derivation seems to parallel the one in which Newton, a century earlier, had derived the mechanism of nature from the God-given or innate properties of the individual physical atom.

Even these few disparate and undeveloped examples indicate that with the creation of the Newtonian universe our story has come full circle. What the Aristotelian universe had done for earth-centered astronomy the Newtonian universe was to do for Copernican astron-
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omy. Each was a world view that tied astronomy to other sciences and related it to nonscientific thought as well; each was a conceptual tool, a way of organizing knowledge, evaluating it, and gaining more; and each dominated the science and philosophy of an age. Having traversed this circle from world view to world view, we may at last realize the sense in which it turns upon Copernicus’ astronomical innovation. The conception of a planetary earth was the first successful break with a constitutive element of the ancient world view. Though intended solely as an astronomical reform, it had destructive consequences which could be resolved only within a new fabric of thought. Copernicus himself did not supply that fabric; his own conception of the universe was closer to Aristotle’s than to Newton’s. But the new problems and suggestions that derived from his innovation are the most prominent landmarks in the development of the new universe which that innovation had itself called forth. The creation of the need and the aid supplied in its fulfillment are the contributions to history that constitute the Copernican Revolution.

Its historical contributions do not, however, exhaust the Revolution’s significance. Because it illustrates the continuing cyclic process by which knowledge grows, the Copernican Revolution has a larger importance as well. The last two and one-half centuries have proved that the conception of the universe which emerged from the Revolution was a far more powerful intellectual tool than the universe of Aristotle and Ptolemy. The scientific cosmology evolved by seventeenth-century scientists and the concepts of space, force, and matter that underlay it, accounted for both celestial and terrestrial motions with a precision undreamed of in antiquity. In addition, they guided many novel and immensely fruitful research programs, disclosing a host of previously unsuspected natural phenomena and revealing order in fields of experience that had been intractable to men governed by the ancient world view. These are permanent achievements. As long as the continuous tradition of Western learning survives, scientists will be able to explain the phenomena first elucidated by Newtonian concepts, just as Newton was able to explain the more restricted list of phenomena previously elucidated by Aristotle and Ptolemy. That is how science advances: each new conceptual scheme embraces the phenomena explained by its predecessors and adds to them.

But though the achievements of Copernicus and Newton are per-

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manent, the concepts that made those achievements possible are not. Only the list of explicable phenomena grows; there is no similar cumulative process for the explanations themselves. As science progresses, its concepts are repeatedly destroyed and replaced, and today Newtonian concepts seem no exception. Like Aristotelianism before it, Newtonianism at last evolved—this time within physics—problems and research techniques which could not be reconciled with the world view that produced them. For half a century we have been in the midst of the resulting conceptual revolution, a revolution that is once again changing the scientist’s (though not yet the layman’s) conception of space, matter, force, and the structure of the universe. Because they provide an economical summary of a vast quantity of information, Newtonian concepts are still in use. But increasingly they are employed for their economy alone, just as the ancient two-sphere universe is employed by the modern navigator and surveyor. They are still a useful aid to memory, but they are ceasing to provide a trustworthy guide to the unknown.

Therefore, though more powerful than its predecessors, the Newtonian universe is not proving more final. Nor is its history, considered as one of many chapters in the development of human thought, very different in structure from that of the earth-centered universe which Copernicus and Newton destroyed. This book is one long chapter in a continued and continuing story.
sun was often recognized, all ancient and medieval estimates of this cosmological dimension remained vastly too small.

Because it depends only upon the relative positions of earth, moon, and sun, Aristarchus' techniques for determining size and distance can be applied with equal accuracy or inaccuracy in the Ptolemaic and Copernican universes. The ancient determinations of astronomical dimensions could, therefore, have no direct role in the Copernican Revolution. But they did have several indirect ones, all of which helped to strengthen the Ptolemaic system. The possibility of making astronomical measurements illustrated the great fruitfulness of the Aristotelian-Ptolemaic universe. In addition, the results of the measurements helped to make the ancient cosmology seem real by increasing the concreteness with which its structure was specified. Finally, and most important, the measurement of the distance to the moon provided an astronomical yardstick which, during the Middle Ages, was used to provide an indirect measure of the size of the entire universe.

As indicated early in Chapter 3, medieval cosmologists often supposed that each crystalline shell was just thick enough to contain the epicycle of its planet and that the shells as a group nested so that they filled all of space. Using these hypotheses mathematical astronomers were able to determine the relative sizes and thicknesses of all the shells. These relative dimensions were then converted to earth diameters, stades, or miles, by using Aristarchus' method of determining the distance to the moon's sphere. A typical set of the cosmological dimensions that resulted was included in the original discussion. It indicates the detail with which the universe was investigated and understood by pre-Copernican scientists.

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Chapter 1. The Ancient Two-Sphere Universe

Chapter 2. The Problem of the Planets

Chapter 3. The Two-Sphere Universe in Aristotelian Thought
2. Ibid., pp. 243-253 (296b8-298a13).

Chapter 4. Recasting the Tradition: Aristotle to the Copernicans
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9. Ibid., IV, 272. In translating this and the following passages from Oresme's commentary I have often been guided by the longer English selection in the mimeographed pamphlet, "Selections in Medieval Mechanics," prepared by Marshall Clagett of the University of Wisconsin and kindly made available to me by its author. Professor Clagett's translations from Oresme and many other medieval scientific writers will soon appear under the title Mechanics in the Middle Ages.

10. Ibid., p. 273.

11. Condensed with permission from Marshall Clagett's "Selections in Medieval Mechanics" (see n. 9), pp. 35–39. The original is Jean Buridan, Quaestiones super octo libros physicorum (Paris, 1509), Book VIII, Question 12. I have introduced a few purely stylistic changes and dropped one set of italics.


Chapter 5. Copernicus' Innovation

1. All the quotations in Chapter 5 are from the Preface and Book I of Copernicus' De Revolutionibus Orbium Caelestium (1543). The translation was prepared by John F. Dobson and Selig Brodetsky and published as Occasional Notes of the Royal Astronomical Society, vol. 2, no. 10 (London: Royal Astronomical Society, 1947). In reprinting the translation I have consistently replaced the word "orbit" by either "sphere" or "circle" (see Edward Rosen, Three Copernican Treatises [New York: Columbia University Press, 1939], pp. 13–16, for the difficulties inherent in Copernicus' use of the Latin orbis). In perhaps a dozen other

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1. Quoted by Francis R. Johnson, Astronomical Thought in Renaissance England (Baltimore: Johns Hopkins Press, 1937), p. 207. I have modernized spelling and punctuation in this and many of the other quotations in this chapter.

2. Ibid., pp. 188–189, from the translation (1605) by Joshua Sylvester.


5. Ibid., pp. 126–127, from Melanchthon's Ininita Doctrinae Physicace.

6. Ibid., p. 127.


Chapter 7. The New Universe


3. Ibid.
