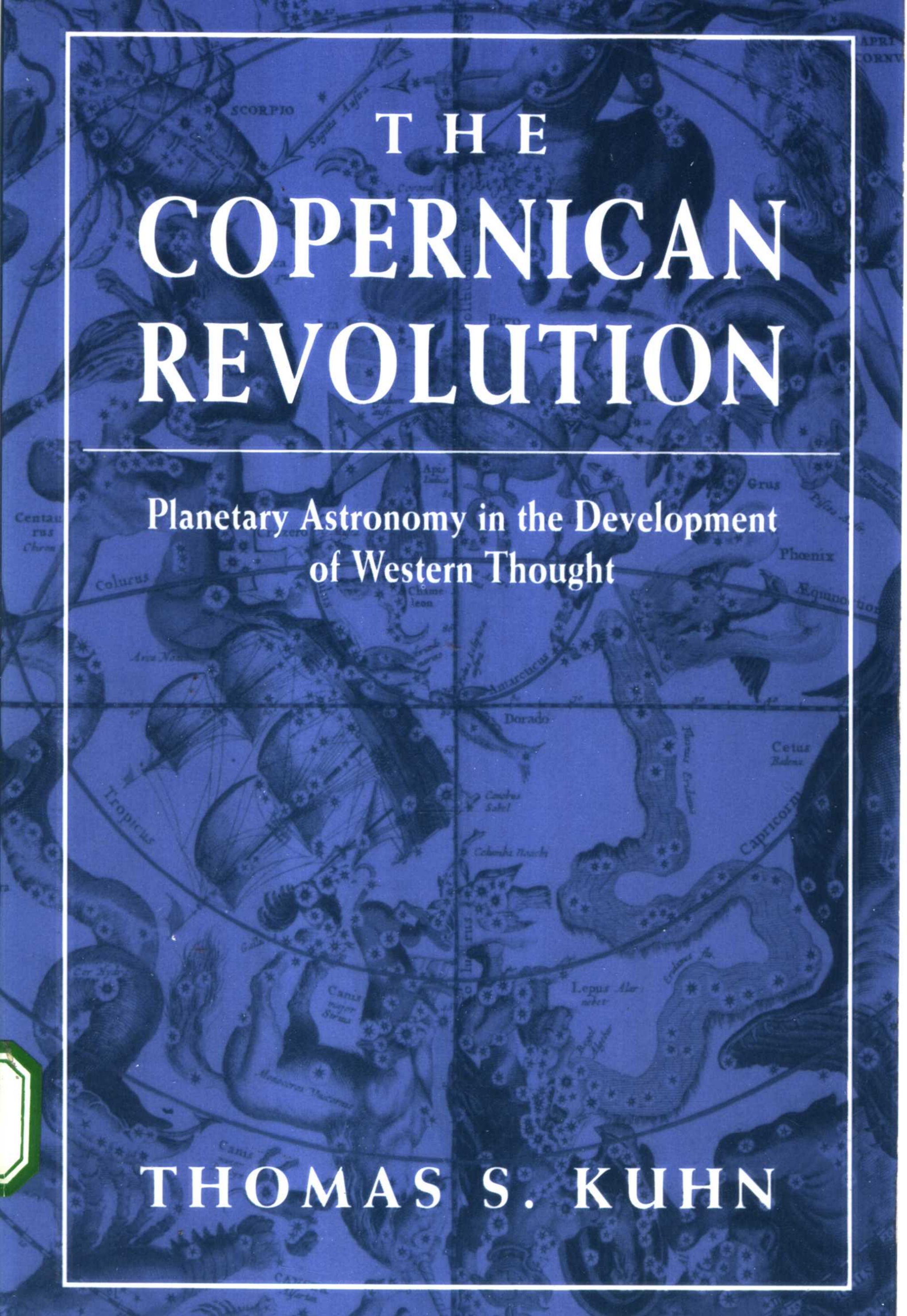

THE COPERNICAN REVOLUTION

Planetary Astronomy in the Development of Western Thought

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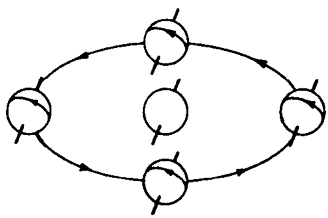

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PREFACE

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 display 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. Arnolfo 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 forebearance 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.

FOREWORD

In Europe west of the Iron Curtain, the literary tradition in education still prevails. An educated man or woman is a person who has acquired a mastery of several tongues and retained a working knowledge of the art and literature of Europe. By a working knowledge I do not refer to a scholarly command of the ancient and modern classics or a sensitive critical judgment of style or form; rather, I have in mind a knowledge which can be readily worked into a conversation at a suitable social gathering. An education based on a carefully circumscribed literary tradition has several obvious advantages: the distinction between the 5 to 10 percent of the population who are thus educated and the others makes itself evident almost automatically when ladies and gentlemen converse. For those who truly enjoy art, literature and music, there is a comforting sense of solidarity. For others who feel compelled to enter into a discussion of these subjects, the area of maneuver is conveniently limited; not too much effort is required to keep fresh a portion of the knowledge painfully acquired at school. The price of admission to the cultural tradition of a European nation is paid once and for all when one is young. Theoretically, this price is eight or nine years of hard work in special schools whose curricula are centered on the languages and literature of Greece and Rome. I say theoretically, since in practice the study of modern languages has in this century made inroads on the study of Greek and to some extent on a knowledge of Latin as well. But even these changes have not fundamentally altered the basic idea of education for the few as being the consequence of long years of school work devoted to the study of languages and the literature of Europe.

There have been attacks on this type of education off and on for a century at least. The claims of the physical sciences for a greater share of the curriculum have been pressed and such claims have usually been associated with demands for the substitution of modern languages for the ancient. The place of mathematics has hardly been at issue, since a thorough study of mathematics, including the calculus, has long been accepted as a matter of course in all the curricula of those special schools which prepare a student to enter the university. Several generations ago, as a clear-cut alternative to the classical curriculum, a course of study was suggested which would be based on physics, chemistry, mathematics, and modern languages. But the proponents of the classical course are still vigorous and effective. In Germany, at least, a series of compromises seems to have been the result of the argument. But because of the importance attached to a study of languages, it is hardly too much to say that the literary tradition still dominates. Even in those schools which devote the most time to science, it would hardly be correct to say that the scientific tradition had replaced the literary. Rather, one might say, in varying degrees German students entering a university have acquired a considerable amount of information about the physical sciences. But whether such knowledge subsequently affects the attitude of those who do not proceed with a scientific education is at least an open question. There seems little or no concern with changing educational methods so that the nonscientist will acquire a better understanding of science. Indeed, it would not be strange if those whose education was primarily literary would question whether understanding science was a matter of importance to anybody but scientists or engineers.

In the United States the European literary tradition as a basis for education disappeared almost a hundred years ago, or rather was transformed beyond recognition. But it has not been replaced by an education based on the physical sciences, mathematics, and modern languages. Some would say there has simply been no replacement. At all events, there have been repeated attempts to provide some broad base for the cultural life of the nation – broad enough to include the physical, biological, and social sciences as well as the Anglo-Saxon literary tradition and concern with art forms from various civilizations. Whether such attempts, directed toward producing a future citizen of a democracy who will be an enthusiastic participant in the nation's developing culture, have created a medium sufficiently nutrient for the life of the spirit in America may be a question. But no one can deny that those responsible for the attempts have, with few exceptions, endeavored to find a suitable place for the scientific tradition.

Experience has shown, however, both in the United States and in the modern schools of Europe, how difficult it is to place the study of science on anything like the same footing as the study of literature or art or music. A scientist or engineer may be able to participate in a stimulating manner in a discussion of pictures or books or plays, but it is very hard indeed to keep a conversation going about physical science in which the majority of the participants are not themselves scientists or engineers. (And while I should be the first to deny that facility in conversation was a goal of education, nevertheless listening in on a social gathering may be a permissible diagnostic method.)

It is quite clear that studying science and studying literature in school or college do not leave the same sort of residue in the student's mind. A knowledge of the chemistry of metals and a knowledge of Shakespeare's plays are two entirely different kinds of knowledge as far as the needs of a human being are concerned. Of course, it is not necessary to pick an example from the natural sciences; for the "chemistry of metals" in the preceding sentence one could quite as well substitute the words "Latin grammar." Expressed in very simple terms, the difference lies in the fact that Shakespeare's plays have been and still are the subjects of endless debates in which the style and the characters have been criticized from every conceivable angle, and strong words of admiration and condemnation are constantly to be heard. No one either admires or condemns the metals or the behavior of their salts.

No, something more than a study of science as a body of organized knowledge, something more than an understanding of scientific theories is required to make educated people ready to accept the scientific tradition alongside that literary tradition which still underlies even the culture of the United States. This is so because the difficulties of assimilating science into Western culture have increased with the centuries. When in the time of Louis XIV scientific academies were formed, new discoveries and new theories in science were far more accessible to educated persons than today; the situation was the same as late as the Napoleonic Wars. Sir Humphrey Davy fascinated London society at the beginning of the 19th century by his lectures on chemistry illustrated by spectacular experiments. Fifty years later Michael Faraday delighted audiences of young and old who came to hear him in the auditorium of the Royal Institution in London; his lectures on the chemistry of the candle are classic examples of popularizing science. In our own times there has been no lack of attempts along similar lines; but the obstacles to be overcome have grown with the years. Spectacular lecture-table experiments no longer astonish and please sophisticated audiences as they once did; large-scale engineering outplays them almost daily. The scientific novelties of the current year are too numerous as well as too complicated to form a topic of conversation among laymen. The advances are made so rapidly and on so many fronts that the layman is bewildered by the news; furthermore, to have any comprehension of the significance of a scientific break-through one needs to be well versed on the state of the science in question before the successful attack was launched. Even those trained in one branch of science find it difficult to understand what is going on in a distant field. For example, physicists are hardly in a position to read even summary papers written by geneticists for other geneticists, and vice versa. For the large group of people with scientific and engineering training who wish to keep abreast of the progress of science in general, there are some excellent periodicals, and useful books are published from time to time. But I doubt very much if this effort to popularize science reaches those who are not directly connected with the physical or biological sciences or their application. And some attempts at popularization are so superficial and sensational as to be of no value for the purposes of providing a basis for the understanding of science by nonscientists.

In the last ten or fifteen years there has been growing concern in American colleges as to the place of the physical and biological sciences in the curriculum. The orthodox first-year courses in physics, chemistry, and biology have been felt by many to be unsatisfactory for those students who do not intend to enter into an intensive study of science, engineering, or medicine. Various proposals have been made and various experiments tried involving new types of scientific courses which would be part of a liberal arts or general education program. In particular, more emphasis on the history of science has been recommended and in this recommendation I have heartily joined. Actually, experience with one type of historical approach in Harvard College for several years has increased my conviction as to the possibilities inherent in the study of the history of science, particularly if combined with an analysis of the various methods by which science has progressed. While recognizing the educational value of an over-all survey of the history of science in the last 300 years, I believe more benefit can be obtained by an intensive study of certain episodes in the development of physics, chemistry, and biology. This conviction has found expression in a series of pamphlets entitled "Harvard Case Histories in Experimental Science."

The cases considered in the Harvard series are relatively narrowly restricted in point of both chronology and subject matter. The aim has been to develop in the student some understanding of the interrelation between theory and experiment and some comprehension of the complicated train of reasoning which connects the testing of a hypothesis with the actual experimental results. To this end an original scientific paper is reprinted and forms the basis of the case; the reader is guided by comments of the editors to follow as far as possible the investigator's own line of reasoning. It is left to the professors who use these pamphlets to fit the case in question into a larger framework of the advance of science on a broad front.

The Harvard Case Histories are too limited in scope and too much concerned with experimental details and analysis of methods for the general reader. Furthermore, though the episodes chosen are all of them important in the history of physics, chemistry, and biology, their significance is not at once apparent to the uninitiated. The reader will soon be aware that the present volume does not suffer from these defects. Everyone knows of the impact on Western culture of the change from an Aristotelian universe centered on the earth to the Copernican universe. Professor Kuhn is concerned not with one event in the history of science but with a series of connected events influenced by and in turn influencing the attitude of learned men far removed in their interests from the field of astronomy itself. He has not set himself the relatively easy task of merely retelling the story of the development of astronomy during the revolutionary period. Rather he has succeeded in presenting an analysis of the relation between theory and observation and belief, and he has boldly faced such embarrassing questions as why brilliant, devoted, and completely sincere students of nature should have delayed so long in accepting the heliocentric arrangement of the planets. This book is no superficial account of the work of scientists; rather it is a thorough exposition of one phase of scientific work, from which the careful reader may learn about the curious interplay of hypothesis and experiment (or astronomical observation) which is the essence of modern science but largely unknown to the nonscientist.

It is not my purpose in this foreword, however, to attempt to present in capsule form a summary of the lessons on understanding science to be derived from reading what Professor Kuhn has written. Rather, I wish to register my conviction that the approach to science presented in this book is the approach needed to enable the scientific tradition to take its place alongside the literary tradition in the culture of the United States. Science has been an enterprise full of mistakes and errors as well as brilliant triumphs; science has been an undertaking carried out by very fallible and often highly emotional human beings; science is but one phase of the creative activities of the Western world which have given us art, literature, and music. The changes in man's views about the structure of the universe portrayed in the following pages affect to some degree the outlook of every educated person of our times; the subject matter is of deep significance in and by itself. But over and above the importance of this particular astronomical revolution, Professor Kuhn's handling of the subject merits attention, for, unless I am much mistaken, he points the way to the road which must be followed if science is to be assimilated into the culture of our times.

JAMES B. CONANT

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THE ANCIENT TWO-SPHERE UNIVERSE

Copernicus and the Modern Mind

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

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

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

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

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

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

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

The mutability of its fundamental concepts is not an argument for rejecting science. Each new scientific theory preserves a hard core of the knowledge provided by its predecessor and adds to it. Science progresses by replacing old theories with new. But an age as dominated by science as our own does need a perspective from which to examine