PHYSICS AND THE PHYSICAL UNIVERSE 2ND ED.

JERRY B. MARION

Physics and the Physical Universe

Second Edition

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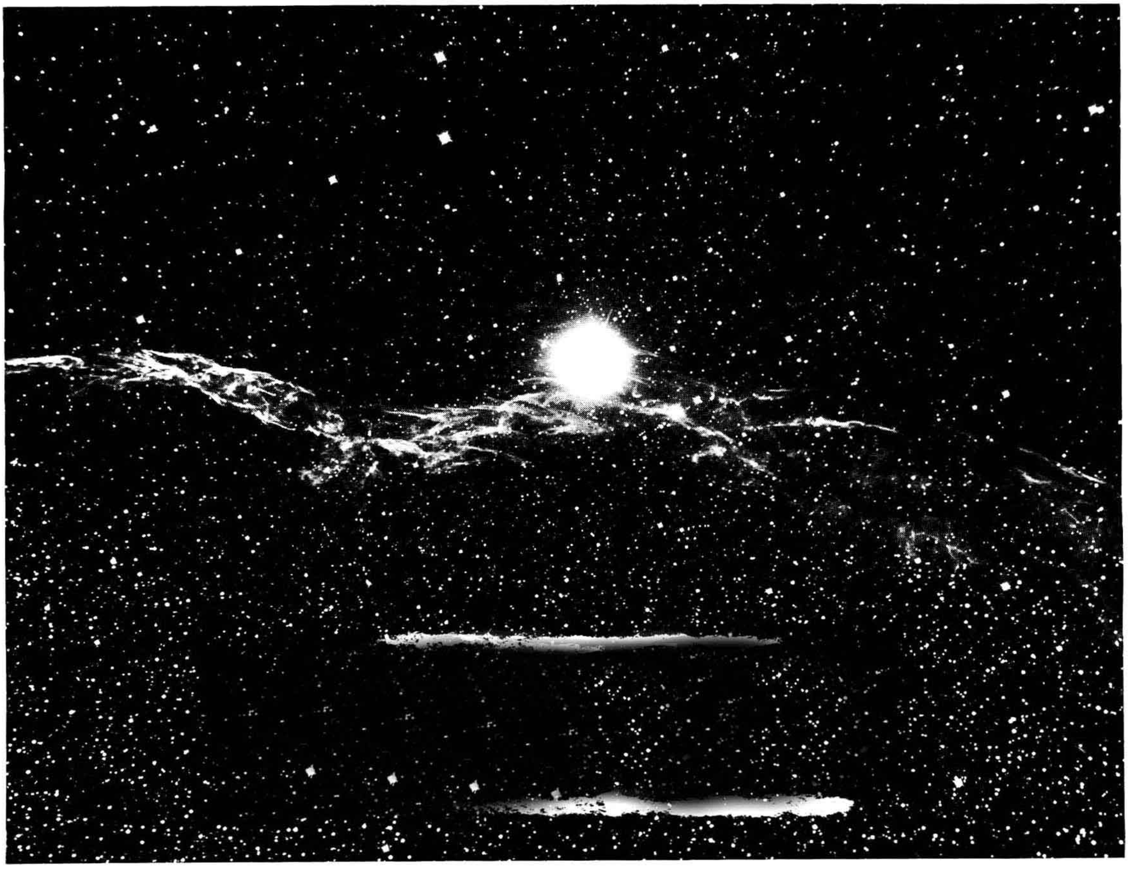

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Physics and the Physical Universe

About the Author

Jerry B. Marion was born in Mobile, Alabama, on December 10, 1929. He received his B.A. at Reed College in 1952, and his Ph.D. at Rice University in 1955. He has taught at the University of Maryland (1957–   ). In 1973 he was the recipient of the Washington Academy of Sciences Teaching of Science Award. In 1955–1956 he was at Caltech as a National Science Foundation Fellow, in 1965 to 1966 as a Guggenheim Fellow at Caltech, and is now a Fellow, American Physical Society. He is a consultant to several industrial organizations and government agencies. He has published research articles dealing with nuclear physics, monographs, and textbooks.

Preface

We live today in a scientific world. Wherever we look we readily see the evidence of the scientific and technological underpinning of our society. Science is a *real* part of the *real* world—and it will remain so. Consequently, no one who hopes to understand or to influence the world he lives in can do so without some appreciation of science and the scientific basis of modern technology.

In the world of the 1970's we must reassert science as a fundamental channel for inquiry into the many basic and unanswered questions of our time. Some of these questions lie not in physics, at least not in the strict sense, but in related fields: astrophysics, geoscience, and the life sciences. Today's student of physics must be made aware of these implications and attention must be given to the interfaces between the various sciences.

It is my hope that, in this introductory physics text, I have succeeded in making it possible to present the subject in this comprehensive light. This book is designed to guide the student to the basic ideas of physics and to explore some of the modern scientific concepts that have emerged in the mid-twentieth century. The emphasis is on contemporary thinking in physics—ideas concerning the structure and the constituents of matter (the *micro*world) as well as modern notions of astronomy, astrophysics and cosmology (the *macro*world). These subjects and the connection between the physical microworld and the life sciences are the topics that are exciting and challenging today. They are, as well, the topics that will shape our future science and technology. No longer is it sufficient for the educated citizen to be aware of Newton's laws and the elementary ideas of gravity and electricity; he must also be acquainted with the new concepts that are emerging from the science of today.

It is necessarily impossible in a relatively short and non-mathematical survey to discuss more than a small fraction of the immense quantity of important ideas in physics. This book represents a synthesis of compromises, in that the choice has been made to treat only briefly or to eliminate entirely many topics in classical physics that seem not directly related to modern physics. In their place has been included a proportionately larger amount of material from areas of contemporary physics, astrophysics, and cosmology. One feature of this book which I hope is both evident and useful is the logical and gradual progression of the level of sophistication required to understand and to appreciate the series of concepts presented.

This text is a part of a larger whole which, taken together, will serve to present a more complete picture of physics and the physical universe. There is available a book of selected readings from the literature of physics (*A Universe of Physics*) that generally follows the organization of the text; it contains historical, biographical, and descriptive articles from a wide variety of sources. There is also available a more-elaborate-than-usual instructor's manual and a student study guide of comparable quality.

In this new edition, a number of changes, additions, and deletions have been made. Wherever appropriate, up-to-date information has replaced outmoded data or interpretations. Also, CGS units have been completely eliminated in favor of MKS units. (Some British notation has been retained in the early chapters to assist the reader in the change to the exclusive use of MKS units in the later chapters.) Some of the discussions have been shortened and made more clear. Short sections have been added on geometric optics, electrical circuits, and the biological effects of radiation. These additions have been accommodated by compressing the discussions of nuclei and elementary particles and incorporating this material into a single chapter, "Nuclei and Particles." Finally, many of the problems have been changed to provide a wider range of assignments.

I wish to take this opportunity to acknowledge the contribution of several persons to the successful completion of this book. Professors G. J. Stephenson, Jr., P. DiLavore, N. S. Wall, and F. C. Young provided extremely helpful criticism of the manuscript in various stages of development. Donald Deneck of John Wiley and Sons gave enthusiastic support to the project from its inception. Several secretaries, particularly Mrs. Elizabeth Lee, typed the several drafts with great efficiency. Thanks are also due the numerous students who used this material in its various mimeographed forms and made many helpful suggestions.

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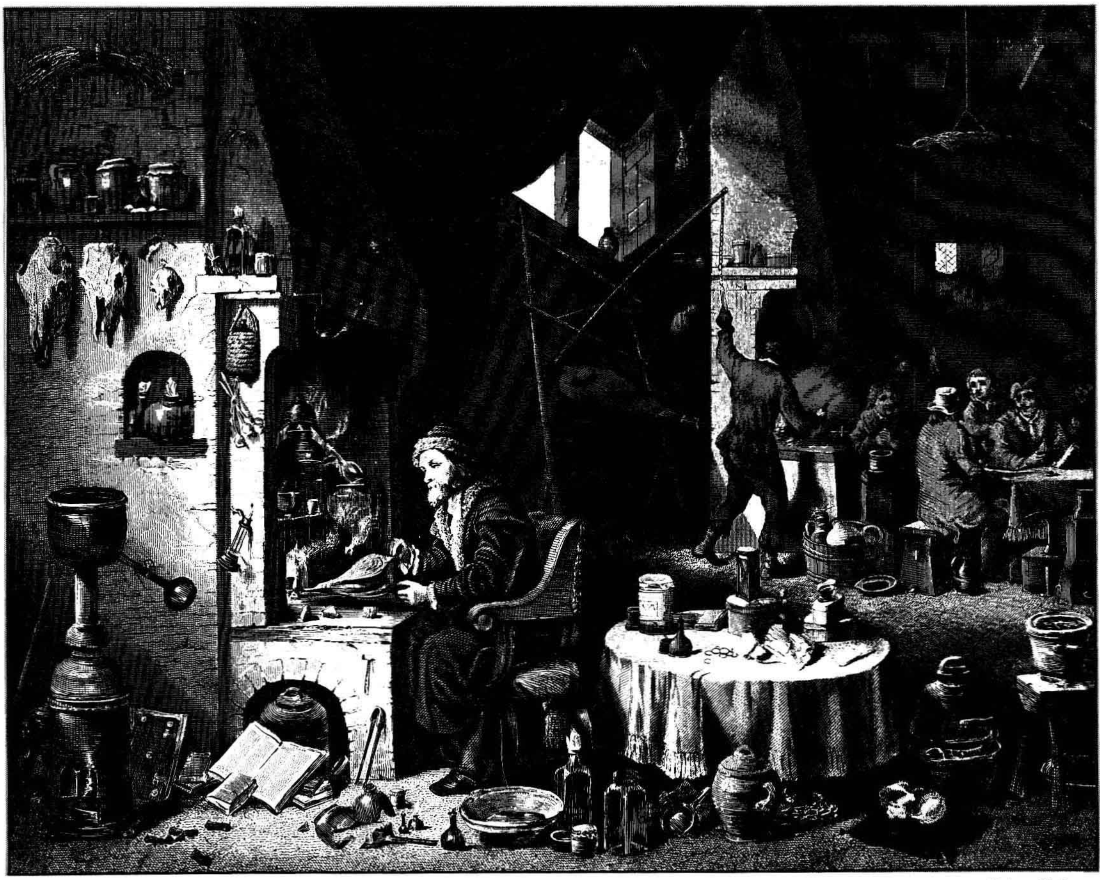

The Chemist

Culver Pictures

Introduction
1.1 *What Is Physics?*
1.2 *Why Is Physics Important?*
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Summary of Important Ideas
Questions
Problems

The science of physics is a growing, changing body of knowledge about the way in which Nature behaves. The historical phases of development in physics can be divided (somewhat arbitrarily) into the *classical, modern,* and *contemporary* periods. Before the end of the 19th century, a detailed knowledge had been acquired of such subdisciplines of physics as mechanics, thermodynamics, electromagnetism, optics, and hydrodynamics. By about 1900, the theoretical descriptions of these areas seemed to be essentially complete and it appeared that there were no more basic discoveries to be made. Collectively, this subject matter is referred to as *classical physics.*

The last few years of the 19th century and the first three decades of the 20th century produced a series of startling new ideas in physics. During this period *radioactivity* was discovered and then used to probe the core of the atom. The development of the theory of *relativity* forced us to examine carefully and to modify our previous views of space and time. And *quantum theory* was formulated from our attempts to describe the inner workings of atomic systems. These decisive years, during which the entire complexion of physics research was changed, we call the era of *modern physics.*

The 1930s witnessed the first observation of radio emissions from stars, the discoveries of the neutron and fission, and the identification of the first elementary particle not found naturally in atoms. Discoveries such as these led to a tremendous outpouring of results in all of the new fields of physics—a growth that continues to the present time. These developments and the new ideas and discoveries to which they have given birth constitute *contemporary physics.*

In the first part of this book we concentrate on the ideas of classical physics. These concepts will provide the necessary background for the discussions of topics in the areas of modern and contemporary physics. In the latter half of the book we will see how these newer developments have been applied, not only in physics and technology, but also in chemistry, astronomy, and in biology.

1.1 *What Is Physics?*

THE STUDY OF THE LAWS OF NATURE

A few hundred years ago the entire body of scientific knowledge was sparse enough that one person could be familiar with most of the essential ideas. Indeed, the scientist of that day was termed a *natural philosopher,* one who studied all facets of natural science. The accumulation of scientific information since those Renaissance days has been so rapid that the natural philosopher (the *compleat* man) has long since ceased to exist. Instead, we have physicists, chemists, biologists, zoologists, geologists, and several dozen other designations for the working scientists of today. However, it is still our goal to unify the separate disciplines of science. When our understanding of Nature is more complete, we shall be more able to appreciate the connection between physics and biology, between chemistry and geology, and between meteorology and oceanography.

The *physicist* seeks, first, to understand the way in which the most elementary systems in Nature really operate. The discoveries made by the physicist not only broaden our view of fundamental processes, but frequently are of crucial importance in the advancement of other sciences. The development of quantum theory, for example, permitted the chemist to understand the wide variety of facts that had been gathered about chemical structures and chemical reactions. The rules that the physicist formulated concerning the propagation of sound waves in solid materials allowed the geologist to use seismological techniques for the investigation of the interior of the Earth. The basic laws of fluid flow, developed more than a hundred years ago, are used by meteorologists and oceanographers in their studies of the movement of air and water masses. The laws of physics determine all physical processes. We have discovered some of these laws—others still elude us.

PHYSICS BEGINS WITH SIMPLE SYSTEMS

Sciences such as geology, meteorology, or physical oceanography attempt to describe the general behavior of very complex systems. Physics, on the other hand, first examines the most elementary systems but in great detail. Thus, while a geologist might be concerned with the description of the process of forming a mountain of rock, the physicist must approach problems of matter in the solid state with a thorough understanding of the inner workings of a simple atom, such as hydrogen. Only then can he progress to the study of the more complicated hydrogen molecule and then to systems of greater complexity, such as matter in the solid state. At each stage of this procedure, the physicist encounters new fundamental problems that must be solved before proceeding to the next step. Progress in physics is made in stages, by building on earlier results, by utilizing the insights gained in previous investigations, by asking new and more penetrating questions, and by sharpening the answers to old questions. In this way we gradually accumulate an overall picture of the way in which Nature behaves.

SERENDIPITY

Sometimes physics is pure luck. There is always the chance that while studying a certain problem there will come, quite by accident, some important new discovery. When Galileo was using his newly invented telescope to study the planets, there suddenly appeared, viewed by man for the first time, four moons circling the planet Jupiter. And Becquerel *just happened* to discover radioactivity when he developed some photographic film on which he has placed some pitchblende (uranium ore) some weeks earlier. Of course, we cannot rely on luck to provide the answers to all of our questions, but science is an endeavor of discovery and some discoveries do happen by accident. The scientist must always be alert to appreciate and take advantage of a stroke of good fortune.

1.2 *Why Is Physics Important?*

PHYSICS AND TECHNOLOGY

Having generally described what physics is about, we now ask "Why is physics important; what *good* is physics?" The physicist does not create new buildings nor construct new modes of transportation. He does not cure our ills nor provide greater comforts in our homes. Physics deals with the pursuit of knowledge about our Universe, its constituents, and their behavior. However, it *is* true that the architects and engineers who construct our buildings and aircraft make constant use of the laws of mechanics and dynamics as formulated by physicists. Many of the diagnostic and therapeutic techniques used in modern medicine were developed in the physics laboratory. Refrigeration, radio, and television are outgrowths of discoveries by physicists. The discovery of the transistor in a solid-state physics laboratory has led to a new age of miniaturized electronics and also to an increasing reliance on computers in our everyday lives. Without the injection of new ideas that have been produced by physicists our great technological industries would not exist and the level of our society would be stark and primitive. Physics is therefore intimately connected with technology and it is the impact of this association that is the most apparent effect of physics on society today.

PHYSICS AND THE PURSUIT OF KNOWLEDGE

Although its contribution to technology is obvious, there is an equally important *why* to physics. Man does not live by technology alone. The fruits of technology influence him *physically*, but it is decisive to the continuing development of the stature of Man that he have *intellectual* stimulation. Physics—indeed, *any* science—is therefore a legitimate pursuit of the mind, just as is history, or philosophy, or music.

Man has always had a never satisfied curiosity of the unknown. Physics provides him a special kind of adventure into this unknown. It offers the challenge of a new problem, the excitement of the development of a new idea, and the intellectual satisfaction of at last seeing a problem solved. One can imagine the excitement of Isaac Newton when the idea of universal gravitation first occurred to him. Or the thrill that must have been Enrico Fermi's when he finally observed his instruments showing that a fission chain-reaction was taking place for the first time on Earth. And what a sense of triumph Albert Einstein must have experienced seventy years ago when he realized that at that moment he alone understood the connection between space and time.

Explorers have climbed mountains and penetrated jungles, divers have probed the depths of the seas, and we have now begun an era of exploration in space. It is no less of an adventure to search out the secrets of Nature in the laboratory.

1.3 *Physics as an Experimental Science*

THE FINAL TEST IS IN THE LABORATORY

The scientist seeks to learn the "truth" about Nature. In physics we can never learn "absolute truth" because physics is basically an experimental science; experiments are never perfect and, therefore, our knowledge of Nature must always be imperfect. We can only state at a certain epoch in time the extent and the precision of our knowledge of Nature, with the full realization that both the extent and the precision will increase in the next epoch. Our understanding of the physical world has as its foundation experimental measurements and observations; on these are based our theories that organize our facts and deepen our understanding.

Physics is not an armchair activity. The ancient Greek philosophers debated the nature of the physical world, but they would not test their conclusions, they would not experiment. Real progress was made only centuries later, when Man finally realized that the key to scientific knowledge lay in observation and experiment, coupled with reason. The Greeks argued that the heavier of two objects would fall the faster. A simple experiment would have tested this conclusion and shown that it was in error. But it remained for Galileo to resolve the point with his careful measurements and well-constructed logic. Of course, the generation of ideas in physics involves a certain amount of just plain *thinking,* but when the final analysis is made, the crucial questions can only be answered in the laboratory.

PHYSICS DEALS WITH CONTROLLED SITUATIONS

In what way does physics differ from a subject such as history? In both fields we try to analyze events and situations by considering causes and effects. However, a given set of historical circumstances presents itself only once. By using the known facts we deduce the chain of occurrences that led to an important event, and we can sometimes establish motives for the actions. But it makes no sense to attempt to reconstruct history as if a certain event did not happen. One can make the idle speculation that if the Spanish had not been turned back by Sir Francis Drake's fleet in 1588, this book might have been written in Spanish instead of English. But such is sheer fantasy—history did not develop that way and it is fruitless to suppose that it might have.

In physics, on the other hand, if a given set of circumstances produces a specific result, we can indeed ask the question "What would have happened if A had been absent?" To answer such a question we simply set up our apparatus again, with A absent, and perform the experiment once more. Ideally, then, physics deals with precise conditions that can be altered and controlled while the effects on the object under investigation are studied. Our results can be unambiguously stated, based on logical deductions from experimental facts.

THE PHILOSOPHY OF DISCOVERY

The mere accumulation of facts does not constitute good science. Certainly, facts are a necessary ingredient in any science, but facts alone are of limited value. In order to fully utilize our facts, we must understand the relationships among them; we must systematize our information and discover how one event produces or influences another event. In doing this, we follow the *scientific method:* observation, reason, and experiment.

The scientific method is not a formal procedure or a detailed map for the exploration of the unknown. In science we must always be alert to a new idea and prepared to take advantage of an unexpected opportunity.

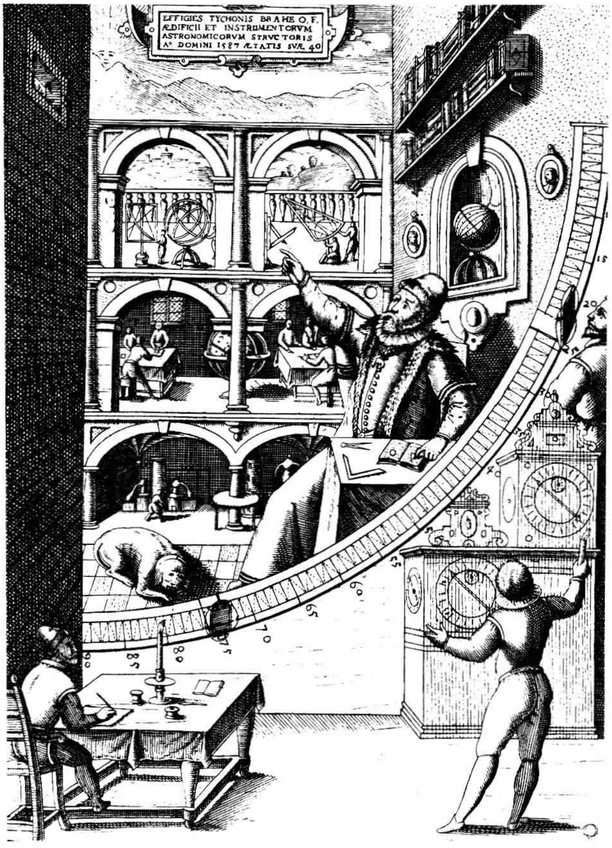

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Fig. 1.1 *Tycho Brahe (1546–1601) and one of his quadrant sextants. Brahe, a Prussian astronomer, used instruments such as this to make extensive and precise measurements of the positions of stars and planets. He was unable to formulate a consistent description of planetary motion, but his meticulous observations were of great value to later astronomers, particularly Kepler (see Fig. 1.2).*

Progress in science occurs only as the result of the symbiotic relationship that exists between observational information and the formulation of ideas that correlate the facts and allow us to appreciate the interrelationships among the facts. The scientific method is actually not a "method" at all; instead, it is an attitude or philosophy concerning the way in which we approach the real physical world and attempt to gain an understanding of the way Nature works.

Johannes Kepler (Fig. 1.2) followed the scientific method when he analyzed an incredible number of observations of the positions of planets in the sky. From these facts he was able to deduce the correct description of planetary motion: the planets move in elliptical orbits around the Sun.

Kepler's procedure—amassing facts and trying various hypotheses until he found one that accounted for all the information—is not the only way to utilize the scientific method. When Erwin Schrödinger was working on the problems associated with the new experiments in atomic physics in the 1920s, he set out to find a description of atomic events that could be formulated in a mathematically beautiful way. Schrödinger deviated from the "normal" procedure of the scientific method. Instead of closely following the experimental facts and attempting to relate them, he sought only to find an aesthetically pleasing mathematical description of the general trend of

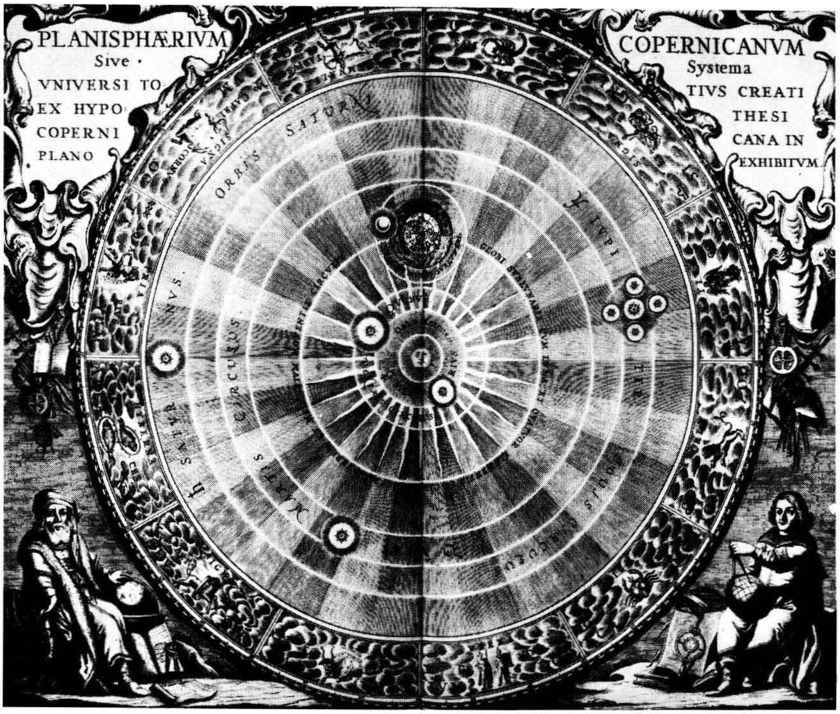

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Fig. 1.2 *Johannes Kepler (1571–1630) and the Copernican description of the solar system which Kepler's calculations firmly established in concept and improved in detail (by showing that the orbits are ellipses).*

the results. This pursuit of mathematical beauty led Schrödinger to develop modern quantum theory. In the realm of atoms, where quantum theory applies, Nature does indeed operate in a beautiful way. At essentially the same time, Werner Heisenberg followed the more conventional approach and formulated an alternative version of quantum theory, which is equivalent in every respect that can be experimentally tested to the theory constructed by Schrödinger.

Therefore, we cannot impose any rigid constraints on the development of science. Different individuals work in different ways. As long as we couple logic and experiment we follow the scientific method.

1.4 *Physical Theories*

THE EVOLUTION OF IDEAS

If we are confronted with a set of facts, it is our task to find the simplest possible way to relate these facts one to another. A successful relationship is called a *theory*. An acceptable theory must account for all the empirical information accumulated about the particular subject and, furthermore, it must be capable of predicting the results of any new experiments that can be performed. (Frequently, a theory will predict effects that are beyond our capabilities to detect at present; in such cases, the tests must await the development of more sensitive techniques.) If any disagreement is found between theory and experiment, then the theory must be modified to account for the new information. Thus, theories evolve by successive refinements.

Physical theories are meant to be tested by confrontations with new facts. Indeed, perhaps the greatest value of a theory is the way in which it can sharply delineate the point at which it fails. No theory can ever be *proved* to be correct; it can only be proved to be *incorrect*. Suppose that certain facts are assembled and a theory is developed which accounts for these facts. With this theory we then make a number of predictions that can be tested by new experiments. If we had made 20 predictions and 19 were verified by experiment, the theory would not be proved correct because it could fail on the twentieth prediction. But such a failure would not be without value, for then we would have a key clue as to where in the theory there was a flaw. Hopefully, this information would enable us to eliminate the fault by modifying the theory and thereby to bring it into agreement with all of the experimental facts.

WHAT CONSTITUTES A "GOOD" THEORY?

The requirements of a good physical theory are:

1. *The theory must be concise.* It is almost always possible to construct a theory that is so complicated that it can account for any given number of facts. But such a theory is highly artificial and offers nothing in the way of intellectual satisfaction. Given two theories that explain a certain body of facts, one complicated and one concise, our preference is always for the concise theory. It is a great triumph to be able to formulate a theory based on only a few postulates and from this theory to extract a wealth of verifiable predictions. The theories of relativity and quantum mechanics are models of brevity, but we are still working out the consequences and putting them to the test of experiment.
2. *The theory must be general.* A theory that is constructed to explain only one or a few facts and is incapable of relating to other facts is useless. A simple (and ludicrous) example of such an *ad hoc* theory is the following.