SECOND EDITION

Earth

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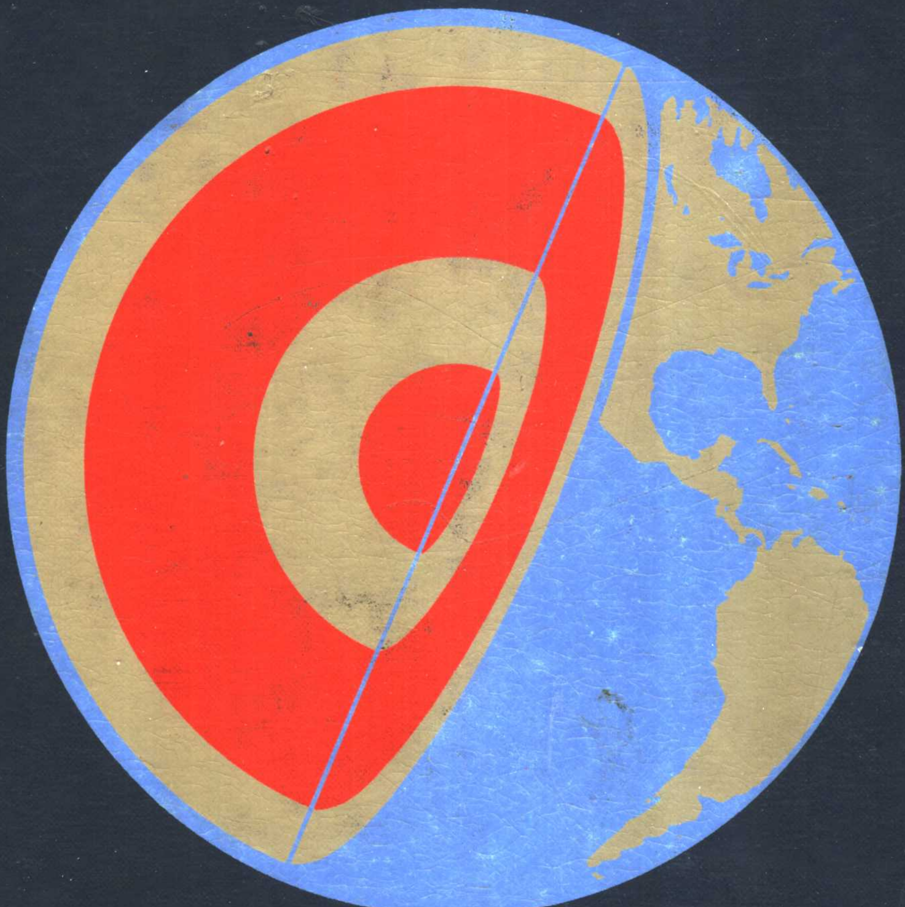

Earth

SECOND EDITION

FRANK PRESS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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PREFACE

TO THE STUDENT

This book is intended for beginning students who have had no previous college science courses and who may not necessarily intend to specialize in geology. For this reason, we have deliberately emphasized a broad view, one that stresses concepts and shows by many examples how science is actually done. Through the use of analogies to familiar processes, the use of "kitchen physics" and "kitchen chemistry" in explanations, and the use of many diagrammatic illustrations, we try to show the evidential bases of geological theories and the strong dependence of geology on the basic scientific disciplines of physics and chemistry. The organic world plays an important role in many geological processes, and thus we introduce some notions of biological processes where appropriate. Yet first and foremost, the book is about geological processes.

As much as possible, we have tried to impart something about what motivates contemporary geologists and about the methods they use, the old ones as well as the new. We want the student to share some of the excitement and exhilaration triggered by the many recent discoveries that have greatly increased our understanding of how this planet works and by the beginnings that have been made in obtaining direct knowledge of how our nearby sister planets compare. Both of us are active in research, but we are also teachers, and believe that the gap between what is new and what is taught to beginners should be narrowed. We take it as a challenge to integrate in a natural way the newest discoveries of plate tectonics, marine geology, geochemistry, geophysics, and lunar and Martian geology into the traditional discussions of such topics as geomorphology, sedimentation, petrology, volcanism, and structural geology.

We have not introduced the very new at the expense of eliminating the essential material, both traditional and modern, that a good course in geology should cover. We introduce the minimum vocabulary necessary to allow free discussion of the concepts involved; this is enough to serve as an introduction to any more-specialized courses that may follow. The coverage of subject matter is sufficiently complete that the book could, if used in its entirety, serve as a foundation on which to build a career in earth science. Nevertheless, our major aim is to reach the many students whose course in geology may be their sole college exposure to science and the study of the Earth. Ultimately they will participate as citizens in governmental policy decisions that pertain to geological questions.

The scientific study of the Earth has never been so important a concern for all peoples as it has become today. The energy, food, and mineral resources of the Earth are now subjects for the daily newspapers and television: the peoples and governments of the world are coming to a new awareness of their importance for the well-being of society. More than at any time in the past century, geologists are today being asked to explain how oil is distributed in the Earth, why we have no domestic supply of some valuable metals, and many other and varied questions. Many of the questions relate to difficulties we encounter in managing our environment while attempting to exploit energy and mineral resources and produce the enormous quantities of industrial and other products required to support a huge and growing population. For this reason, we have shown, in many places in the book, how *knowledge* of the science is linked to its *uses,* both in detailed practical ways and in the making of policy decisions. As geology has become the focus of more attention, it has aroused the curiosity of young people about nature in general. Enrollment in introductory geology courses has increased greatly in the past decade. Today people travel more than ever before, and as they see the diversity of the Earth, they want to understand what they see.

Geology is in a golden age as measured by the impact of the discoveries and new theories of the past ten years that have given us profound new insights into the ways this planet works. For the first time in the modern history of the discipline, an all-encompassing synthesis of much of geological knowledge has been advanced and gained acceptance across a broad spectrum of professionals in the field. That synthesis, plate-tectonic theory, born only ten years ago, has started to mature in the few years since the first edition of this book appeared. As in any major new theory, work stimulated by it has enriched the subject and at the same time introduced complexities in a once-simple idea. Applications of the theory to new areas of the oceans and continents have bred new problems that are being tackled by geologists using a framework of thinking that is still only a decade old, and not settled into a well-worn path of familiar notions.

The impact of plate-tectonic theory on almost every area of geology, geochemistry, and geophysics has been pervasive, but that theory is not the only new development in the science. The discoveries of the past few years in planetary science—in particular, the landing on Mars in 1976—have added greatly to our knowledge of how the solar system evolved and have given us better data for comparison with the planet we live on. This in turn has stimulated a resurgence of work on the earliest rocks of Earth. But these are only a few of the high spots. Every chapter of this book has had to be revised since the first edition; that is the measure of our advancing knowledge in every aspect of the subject.

The startling new developments continue to roll in and challenge our scientific powers and imaginations. That was true when the first edition of this book was published in 1974, and it is true today. Our objective is the same: to give an introduction to this broad field of knowledge that is as up-to-date as the results presented by geologists at the most recent meetings of the Geological Society of America and to present that new material so that it is as understandable as today's newspaper, without oversimplification that would destroy the richness of the discoveries.

We hope that this book will reach many students and introduce them to geology with what we believe is a fresh approach, and impart something of the intellectual excitement, the growing relevance to societal problems, and the esthetics of the subject. If we succeed in this, the large investment we have made in time and energy will all have been worthwhile.

TO THE INSTRUCTOR

We have made each chapter as self-sufficient as possible, so that chapters may be skipped in short courses or be taken up out of sequence according to the instructor's individual taste. (Professor Roger Thomas, in his instructor's guide, has several suggestions along these lines.) We have designed *repetition, review,* and *alternative restatement* into the book with a definite purpose—to enhance learning and to increase flexibility in the way the book is used.

We make extensive use of line drawings and photographs, plus the use of boxed information and other aids to learning, for it is our feeling that these aids will be of considerable value in simplifying otherwise difficult material and will serve to motivate the student. Explanatory sketches, diagrams, and photographs are used in places as substitutes for equations, and help to make up for lack of prior knowledge of other sciences. We also use illustrations as alternative statements of concepts presented in the text and as summaries of material covered earlier. To avoid interrupting the flow of the main text, occasional bits of parenthetical material appear in smaller type in the margins. These brief notes serve as slight amplifications of the text, as interesting sidelights, and as brief comments on some of the extraordinary personalities who have been part of the quest to understand the Earth. In a few places we have used boxes to expand in a more detailed way some materials of the text. These boxes are for the student who wants to understand more deeply some of the background of the subject. They are not necessary for understanding the text; some are pitched at a slightly higher level than the rest of the book.

The introductions at the beginning of the three parts of the book and the brief abstracts at the beginnings of chapters are designed to forecast in a general way the nature of the subject matter, how it fits together, and how it relates to other chapters. Summaries in list form appear at the ends of chapters to serve as systematic reviews of major conclusions. Questions were devised to help the student test his comprehension of the materials either by essay or by solving concrete problems. The bibliographies include *Scientific American* Offprints on closely related subjects, elementary or slightly advanced paperbacks, government reports on specialized topics, and a few readily available technical articles from the geological literature.

This book is divided into three parts. Each part consists of chapters grouped together according to their relations to the major concepts of the Earth's dynamics. Part I groups topics relating to the Earth as an evolving planet and how we study it and its materials. In the first chapter we give a capsule history of the Earth and the first glimpse of the general theory about how it operates. A brief outline of plate tectonics is presented to serve as a guide to succeeding chapters, where ramifications and implications of the theory are discussed with reference to the entire range of geological subjects considered in the book. The second chapter explores time in geology, the relation of process to history, and emphasizes how field observations form the central basis of our knowledge of the geological cycle. The third chapter is concerned with the prime source of information on the Earth: rocks and minerals. The major concepts of mineralogy and petrology are introduced and linked to a brief but systematic discussion of the major rock-forming minerals and the three major rock groups.

Part II covers those aspects of the Earth that are dominated by the external solar heat machine, all of the surface processes that result from the Sun's radiant energy impinging on the surface of the planet, its atmosphere, and oceans. Erosion, transportation, and deposition of chemically altered and physically fragmented rocks, and the resulting sculpture of the surface are discussed in relation to tectonics and the dynamics of the atmosphere and oceans. Part II concludes with a chapter on the interactions of the biological world and Earth's inorganic materials, and how man as a geological agent has been profoundly changing the surface environment.

Part III explores the consequences of the internal heat machine of the Earth, and how it drives major movements of the interior and determines the structure of the whole planet. Internal heat, volcanism, and the kinds of igneous and metamorphic rocks that are produced by thermal processes are the subjects of the first group of chapters. The structure of the interior as deduced from seismology, gravity, and magnetism is then explored in preparation for a detailed systematic explanation of plate tectonics. It is only after this that we come to structural geology, which then can be treated in the context of the large-scale motions of lithospheric plates. Following this is a chapter on what we know of the nature and evolution of the other planets in the solar system, with major emphasis on lunar exploration. The book concludes with a chapter on earth materials as resources, including an extended treatment of energy reserves and the central importance of energy costs in the recovery of all other resources.

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Raymond Siever

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CONTENTS

PART ONE

THE EARTH AS AN HISTORICALLY EVOLVED BODY AND HOW WE STUDY IT

This planet on which we live has undergone constant change throughout a long history. To understand what the Earth is and how it works today, we link direct observation of processes operating at the surface with indirect measurement of forces working in the interior. The fullest knowledge comes from deducing how the planet evolved—from its beginnings to its present state.

Formed almost five billion years ago from a mass of dust rotating around the infant Sun, the Earth grew into a medium-sized planet whose history has been dominated by two driving machines. The first is the internal heat produced by radioactivity inside the Earth. The second is the external heat supplied to the surface by the Sun. The internal heat melts rocks, makes volcanoes, and thrusts mountains upward. The external heat drives the atmosphere and the oceans and causes the erosion of mountains and the reduction of rock to sediment. New methods of studying how the internal and external forces drive the Earth have generated a wealth of new information and raised many exciting new questions. In the past decade, geologists have gradually developed a new unifying theory that relates all of the dynamic Earth processes to the motions of large plates that constitute the outer shell of the planet. Called the theory of plate tectonics, it offers the most comprehensive model that geologists have ever had for explaining how the Earth works.

In the first part of this book we survey the ways in which we study this planet and what we have learned of its origin. These first chapters are a capsule of the book; in them we preview many subjects—particularly the nature of time and the materials of Earth—before they are explored in detail in later chapters.

1

HISTORY OF THE EARTH AND SOLAR SYSTEM

An introduction to the Earth, beginning with a cloud of dust and gas from which the solar system formed a little less than 5 billion years ago, to the birth of the Earth about 4.7 billion years ago, to the planet we know today, with its hospitable atmosphere and rich resources, a planet still active inside—as evidenced by earthquakes, volcanoes, ocean basins that open and close, and continents that drift apart.

THE UNIQUENESS OF PLANET EARTH

"Civilization exists by geological consent, subject to change without notice," said philosopher-historian Will Durant, reminding us of the remarkable circumstances that make this planet congenial to life as we know it. The Earth, after all, is a very special place—and not just because we humans inhabit it. More than a million life forms have developed on this unique spot in the solar system. *Homo sapiens,* the one species with the power of reason, is a rather recent arrival. In the study of geology, we explore not only the Earth as it exists today; we also seek answers to how it was formed, what it was like when first born, how it evolved to the planet of today, and, perhaps most exciting of all, what made it capable of supporting life.

No one knows precisely when the composition and state of the Earth's primitive atmosphere were just right for life to begin and evolve. We do know, however, that the large organic molecules that apparently preceded the evolution of the earliest forms of life could not have formed if the primitive atmosphere contained as much oxygen as the one we now enjoy. Chemists tell us the oxygen would have destroyed them. The Earth's atmosphere and magnetic field acted as a shield against some of the biologically damaging radiation from space, just as they do today. Meteors, unbraked by the cushion of gases, would have bombarded Earth, leaving a crater-pocked, desolate surface that could never be softened by erosion. The atmosphere that exists today not only filters out the greatest part of destructive ultraviolet radiation, but together with the ocean, it stores and redistributes solar energy, thus moderating climate. Without atmosphere and oceans, there would be much more extreme temperature differences between day and night, summer and winter, and equator and pole.

The list of fortuitous conditions so propitious to life is long. Life as we know it is possible over a very narrow temperature interval—essentially within the limits set by the freezing and boiling points of water. This interval is perhaps 1 or 2 percent of the range between a temperature of absolute zero and the surface temperature of the Sun. How fortunate that Earth formed where it did in the Solar System, neither too far from the Sun nor too close to it! And Earth's size was just about right—not so small as to lose its atmos-

It is quite probable that the conditions that would allow life to flourish anywhere in the Universe would not differ much from those that have allowed life to evolve on Earth. This observation led astronomers to propose that other planets, situated about as far from their suns as we are from ours, might also have life.

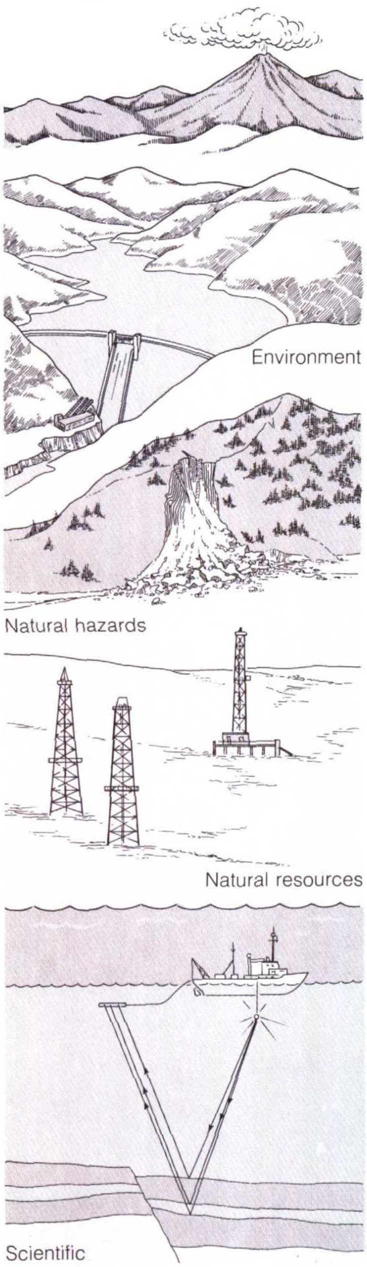

Figure 1-1
Different aspects of geology—nature appreciation, environmental protection, hazard reduction, natural resources, scientific research.

phere because its gravity was too small to prevent gases from escaping into space, and not so large that its gravity would hold on to too much atmosphere, including harmful gases.

We will see that the Earth's interior is a gigantic but delicately balanced heat engine fueled by radioactivity, which has much to do with how the surface evolved. Were it running more slowly, geological activity would have proceeded at a slower pace. The continents might not have evolved to their present form, and volcanoes might not have spewed out the water and gases that became the oceans and atmosphere. Iron might not have melted and sunk to form the liquid core, and the magnetic field would never have developed. The Earth would then have evolved as a cratered, dead planet similar to the Moon. Another scenario can be imagined: if there had been more radioactive fuel and a faster-running engine, volcanic gas and dust would have blotted out the Sun, the atmosphere would have been oppressively dense, and the surface would have been racked by daily earthquakes and volcanic explosions. Perhaps the Earth had such a fast-running era early in its history.

No wonder the Apollo astronauts were so profoundly affected by the view from the Moon of their home planet, with its inviting blue atmosphere and white clouds in contrast to the desolate terrain they could see on the Moon.

ASPECTS OF GEOLOGY

Although geology has ranked as a modern scholarly discipline for only two centuries, man has been curious about the Earth and its origins from the beginnings of pre-history. Stories of creation are invariably found in the sagas and folktales of early civilizations. In doing so, perhaps the ancients derived some feeling of security; perhaps they satisfied their own curiosity by reciting creation myths to their young, as if to put behind them the primeval chaos of an unknown creation. But a common theme was the creation, the bringing into existence, as contrasted with the idea of always having been here.

Nature's Threat. The human need to understand and to be able to explain nature in order to gain protection from her vagaries survives to this day as a major motivation toward the study of geology. Modern man seeks safeguards against nature's threats, which come in the form of earthquakes, landslides, volcanic eruptions, floods, droughts, and the destructive sea waves known as tsunamis. Perhaps even more dangerous are man-made catastrophes, for our unique species has gained the power to trigger earthquakes, foul the atmosphere and oceans, and alter climates to the point of either initiating ice ages or melting the polar ice caps and flooding coastal cities. If man can do these things, so can he eventually predict or control most natural disasters.

Economic Geology. Were it not for the accessibility and diversity of minerals in the Earth's crust, man's cultural level would not have progressed beyond the Stone Age. The discovery of the Earth's mineral wealth is the geologist's task. If we are to extend to the many the affluence enjoyed by the few, let alone maintain our own present standard of living, new mineral deposits must be found. Prospectors have long since found the obvious deposits of iron, copper, tin, uranium, oil, and other important minerals. It is a challenge to geologists to re-explore the world, using new tools and techniques to ferret out undiscovered deposits. New and pressing concerns of geologists are conservation and environmental protection. How can we most efficiently exploit nature's wealth without waste and without devastating the landscape? Somehow we must find answers to these questions.

Scholarly Geology. Geology also has its "pure" aspects for those who work at it, in that it is interesting of and for itself. How a planet is born—the course of its evolution—and how it works today are only partially answered questions. Geologists are motivated to find answers because, like all scientists, they have unbounded curiosity and perhaps even a sense of uneasiness when important natural phenomena remain unexplained. Geologists will be hammering at outcrops, making geologic maps, exploring the sea floor, and scrutinizing Moon rocks as long as mountain-making, continental drift, sea-floor spreading, earthquakes, and other planetary features remain incompletely explained.

Geology for the Poets. Most students who enroll in geology courses have no intention of becoming professional geologists. They elect geology for many reasons. Perhaps they hope to heighten their appreciation of nature by gaining insight into her many ways. Perhaps the current crisis of the environment has induced them to learn more about a key environmental science. Perhaps Norman Mailer expressed their moti-

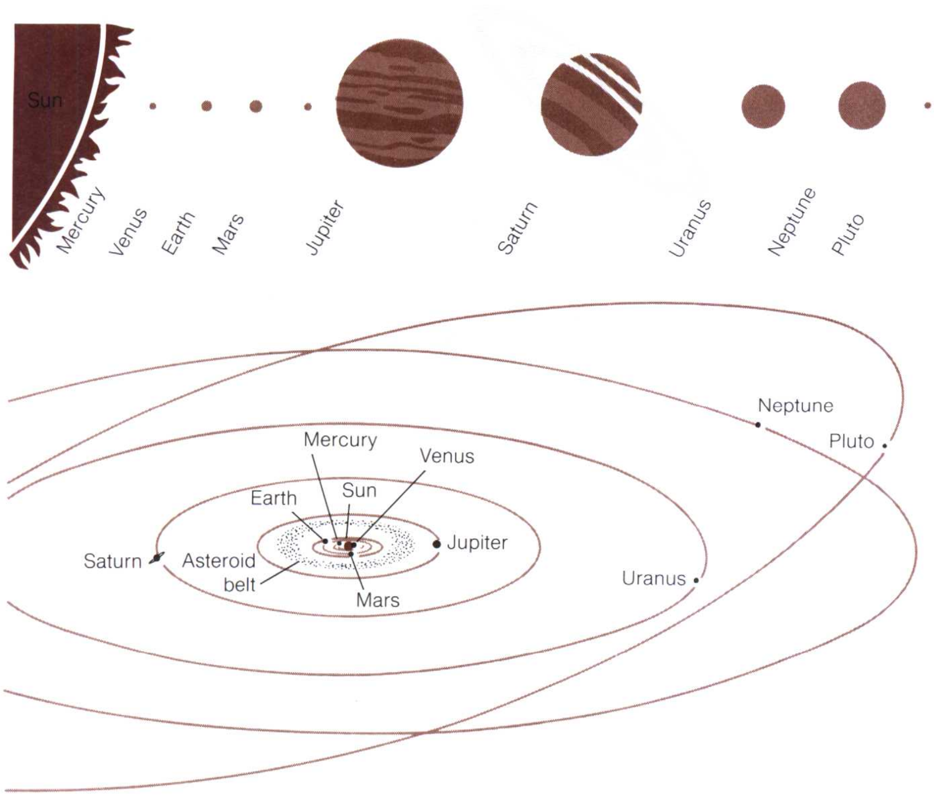

Figure 1-2
The Solar System. Diagrammatic representations of the Sun and planets.

vation when he wrote of the moon flight of the Apollo astronauts: "yes, we might have to go out into space until the mystery of new discovery would force us to regard the world once again as poets."

ORIGIN OF THE SYSTEM OF PLANETS

Let us start at the beginning with the first and most difficult problem: How did the **system of planets** originate? This question has attracted the attention of many of the great philosophers and scientists of the past two centuries. Yet it is a rare geological or astronomical congress that does not witness a fresh debate triggered by the latest experimental data or the newest theoretical advance pertaining to this question.

Explain the Observations. If anyone wishes to enter the lists with a pet hypothesis, the procedure is simple enough. On the basis of logical reasoning, develop a mechanism for the formation of the planetary system—a self-consistent mechanism that will explain the mass and size distribution of the planets, the peculiarities of their orbits, the relative abundances of elements in the planets and the Sun. Useful hints can be gleaned from studies of other stars.

Whatever did happen, beginning about 4.7 billion years ago, when the planets started forming, resulted in several amazing regularities and curious groupings in the solar system:

1. The planets all revolve around the Sun in the same direction, in **elliptical,** but almost circular, **orbits** that lie in nearly the same plane; most of their moons also revolve in the same direction.

2. The planets, except for Venus and Uranus, *rotate* in the same direction as their revolution around the Sun—that is, counterclockwise as one looks from the North pole to the South pole of the Earth.

3. The distance of each planet from the Sun is roughly twice that of the next planet closer to the Sun (an ordering known as the **Titius-Bode rule**).

We will show in Chapter 2 how certain radioactive elements, uranium, potassium, and rubidium, serve as clocks that enable us to chronicle major events in the solar system, such as its beginning 4.7 billion years ago.

4. Although the Sun makes up about 99.9 percent of the mass of the solar system, 99 percent of the **angular momentum** is concentrated in the large planets (see Fig. 1-3 for an explanation of angular momentum).

5. The planets form two groups: the so-called **terrestrial planets,** Mercury, Venus, Earth, and Mars, which form an inner group of small, dense bodies (densities about 4 to 5.5 times that of water); and the **giant planets,** Jupiter, Saturn, Uranus, and Neptune, which are an outer group of large bodies with low densities (between 0.7 and 1.7 times that of water). In some respects—for example, their high gas content and low density—the giant planets are more like the Sun than like the terrestrial planets.

Light is emitted or absorbed in a characteristic way by different elements in gaseous form, as they incandesce. Analysis of light into color components (more accurately, its spectral components) reveals the composition of its source. Thus the yellow color produced when common salt (sodium chloride, NaCl) is burned (vaporized) in a natural gas flame reveals the presence of the element Na.

From chemical analysis of Earth rocks, Moon rocks, and meteorites that reach the Earth from interplanetary space, we surmise that the terrestrial planets are made up mostly ($\pm$90 percent) of four elements: iron, oxygen, silicon, and magnesium. Spectroscopic studies of the Sun show it to be composed almost entirely (99 percent) of hydrogen and helium. Presumably the high abundances of hydrogen and helium are features of the giant planets also.

The Nebular Hypotheses. There has been no dearth of theories of creation over the centuries. The modern approach to the problem, however, began in 1755 when the German philosopher Immanuel Kant hypothesized a primeval, slowly rotating cloud of gas, now called a nebula, which in some unspecified fashion condenses into a number of discrete, globular bodies. In this way Kant neatly explained the consistency of revolution and rotation directions, in that the rotation of the parent nebula is preserved in the rotation of the Sun, the revolution of the planets about the Sun, and the rotation of the planets about their axes—all in the same direction (Fig. 1-4).

Kant's hypothesis, published anonymously, carried an impressive title: *Universal Natural History and Theory of the Heavens, or an Essay on the Constitution and Mechanical Origin of the Whole Universe, Treated According to Newtonian Principles.* The publisher went bankrupt and the stock was seized by the creditors, so that very few copies reached public hands.

The great French mathematician Laplace proposed essentially the same theory in 1796—surprisingly, without the mathematical formulation he was capable of providing. Historians of science will have to resolve the questions of whether Laplace knew of Kant's work and why he chose not to subject his own *nebular hypothesis* to mathematical examination, for had he done so he might have discovered some serious flaws.

According to Kant and Laplace, the original mass of gas cooled and began to contract. As it did, the rotational speed increased (a consequence of the **law of conservation of angular momentum,** illustrated in Figure 1-5) until successive rings of gaseous material were spun off from the central mass by centrifugal force. In the final stages the rings condensed into planets.

Not so, according to the great British physicists James Clerk Maxwell and Sir James Jeans, who showed about one-hundred years later that there was not enough mass in the rings to provide the gravitational attraction for condensation into individual planets. The coup de grâce was delivered at the close of the nineteenth century, when astronomer F. R. Moulton of Chicago showed that the nebular hypothesis violated item 4 above—namely, that the planets have most of the angular momentum. The law of conservation of angular momentum requires each part of a rotating, condensing nebula to hold onto its angular momentum; the Sun, which collected most of the mass, should have gathered up most of the angular momentum of the system. Simply stated, the Sun doesn't rotate fast enough; it should have spun faster, just as the skater in Figure 1-5 spins faster when she pulls in her arms.

Collision Hypotheses. Wanted—a theory, now that Kant and Laplace were in disfavor. Geologist T. C. Chamberlin collaborated on one theory with Moulton, his astronomer fellow professor at Chicago, and revived an early proposal (1749) of Count Buffon of France—the **collision hypothesis.** Stated simply, this hypothesis holds that giant tongues of material were torn from the pre-existing Sun by the gravitational attraction of a passing star. According to Chamberlin and Moulton, these broke into small chunks, or **planetesimals,** which went flying as cold bodies into orbits around the Sun in the plane of the passing star. By collision and gravitational attraction, the larger planetesimals swept up the smaller pieces, and those that survived became the planets. Unfortunately, the several versions of collision theories have fatal weaknesses. According to astronomers, much of the material ejected from the Sun would have come from the interior and would have been so hot, perhaps 1,000,000°C, that the gases would have been dispersed throughout space with explosive violence rather than condensed into planets. Although more angular momentum would have been imparted to the planets by a passing star than by the rotation of a nebula, the amount is still less than that observed. Finally, the vastness of space makes the probability of such a close approach of two stars extremely small.

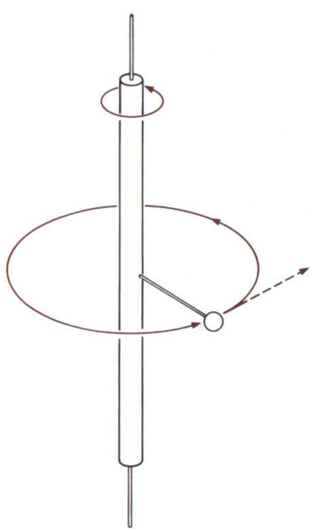

Figure 1-3
Angular momentum, illustrated by the example of a heavy steel ball fastened to the central shaft by a very light rod. Turning the shaft causes the ball to rotate around it. The ball's angular momentum is defined as the product of the mass of the ball, its velocity, and its distance from the rotation axis. [From *New Horizons in Astronomy* by J. C. Brandt and S. P. Maran. W. H. Freeman and Company. Copyright © 1972.]

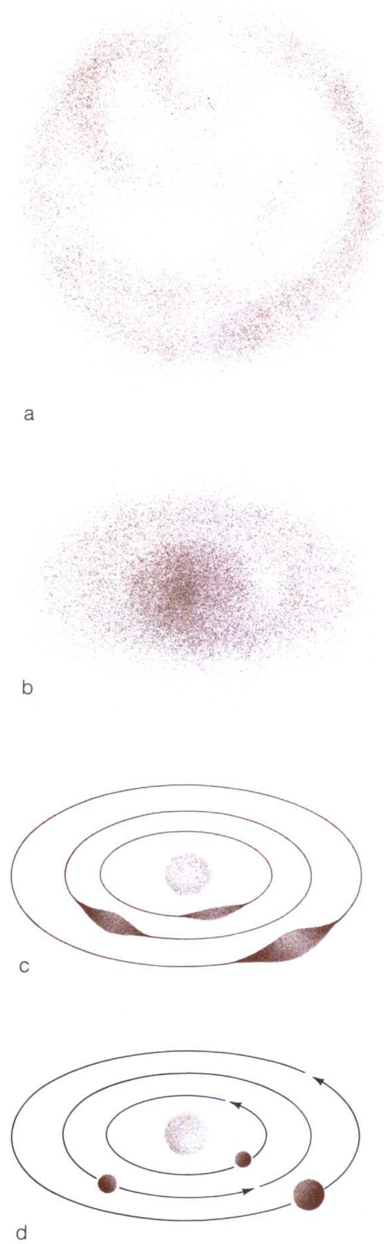

Figure 1-4
Schematic diagram of the nebular hypothesis. (a) A diffuse, roughly spherical, slowly rotating nebula begins to contract. (b) As a result of contraction and rotation, a flat, rapidly rotating disk is produced with concentration of matter in the center. (c) Contraction continues, the proto-Sun is formed, and rings of material are left behind. (d) The material in the rings condenses into planets revolving in orbit around the Sun. [After *New Horizons in Astronomy* by J. C. Brandt and S. P. Maran. W. H. Freeman and Company. Copyright © 1972.]

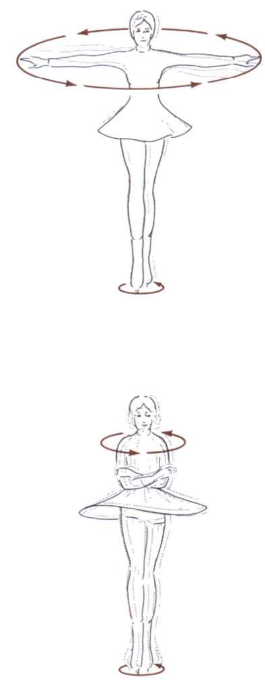

Figure 1-5
Illustration of conservation of angular momentum; when a skater pulls in her arms, she spins at a faster rate. Similarly, when a slowly rotating nebula contracts, its rotation speed increases.

Exciting recent discoveries of such biologically important compounds as ammonia, methane, formic acid, and formaldehyde in interstellar space and of amino acids in meteorites have profound implications for the origin of life on Earth and elsewhere in the universe. Their presence in space shows that the formation of the simple organic compounds, the building blocks of life, is an ordinary accomplishment of galactic evolution.

In June 1977, astronomers at the University of New Mexico and NASA reported a distant star in the constellation Cygnus that shows a pattern of energy radiation that indicates a young disk-shaped star. This may be the first discovery of a solar system caught in the process of birth.

Recent Theories. The thinking of the past few decades has been influenced by the discovery that space is not as empty as had been thought. Astronomical observations have detected, both in interstellar space and in nebulae, rarefied matter consisting of about 99 percent gas and 1 percent dust. The gases are mostly hydrogen and helium; the dust-size particles have compositions similar to those of terrestrial materials, such as silicon compounds, iron oxides, ice crystals, and a host of other small molecules, including organic ones. It is not surprising, then, that recent theories tend to be neo-Laplacian in that they revive the idea of a primordial, rotating cloud of gas and dust whose shape and internal motions were determined by gravitational forces and the forces of rotation. At some moment gravitational attraction became the dominant factor, contraction began, and the rotation speeded up (again, conservation of angular momentum). The cloud tended to flatten into a disk; matter began to drift toward the center, accumulating into the **proto-Sun.** The proto-Sun collapsed under its own gravitation, becoming dense and opaque as the material was compressed. Its internal temperature rose to about 1,000,000°C, at which point "nuclear burning," or fusion, began. More precisely, the Sun began to shine with the initiation of the **thermonuclear reaction** (now unfortunately duplicated on Earth by H-bombs), in which hydrogen nuclei combine under intense pressure to form helium nuclei, releasing a vast amount of energy.

What about the disk of gas and dust enveloping the primitive Sun? How did it form into planets? How did the planets pick up the necessary angular momentum, and what about the differing chemical composition of the planets? There is very little agreement among the experts about the answers to these questions.

A recent nebular-disk model, the *chemical-condensation-sequence* model, is receiving much attention lately because it seems to predict the observed variations of chemical compositions and densities of the planets (Fig. 1-6). Initially, the disk was extremely hot, so that much of its materials were in their gaseous form. As the spinning disk cooled, various solid compounds and minerals condensed out of the gas, forming grains that gradually clumped together into small chunks, or planetesimals. The planetesimals coalesced, the bigger ones with stronger gravity pulling in all the nearly condensed matter. If a planet grew at a distance close enough to the Sun so that it was too hot for certain materials to condense, those materials would be blown away as gases by radiation and by matter streaming from the Sun. (The ejection of matter from the Sun during these early stages was also responsible for slowing its rotation.) Close to the Sun, where temperatures were highest, the first materials to condense were those with high boiling points, such as most metals and rocks. Thus Mercury, the planet closest to the Sun, is the most dense (5.4 times the density of water) because it is richest in iron. The proximity of Mercury to the Sun means that it formed at a temperature so high that iron could condense, whereas the lighter, rock-forming compounds, such as those made of magnesium, silicon, and oxygen, condensed more readily in the "cooler" environments of the terrestrial planets more distant from the Sun. Volatile (easily evaporated) materials, such as water, methane, ammonia, were mostly lost to the terrestrial planets, but could condense into ices in the cold outer reaches of the solar system, perhaps on the satellites of the giant planets. Jupiter and Saturn were big enough, and had gravitational attractions strong enough, to hold on to all of their constituents, thereby retaining the composition of the original nebula—mostly hydrogen and helium, much like that of the Sun.

The preceding should be taken for what it is—a hypothesis, a possible model. Perhaps some of these notions come close to what actually happened: we will know only after much additional work is done, some of it now underway. Nebulae at different stages of development are being studied not only with the familiar optical telescope but also with special devices that magnify x-rays and radio waves. These invisible but detectable waves provide additional information about what goes on in the remote sections of the universe. The first planetary probes have been returning data on the nature and composition of the atmospheres and surfaces of Mercury, Venus, Mars, Jupiter, and the Moon. Mathematicians are developing new tools to improve computer reproduction of the motions of rotating gas-dust clouds and growing planets. All of this activity should in time give us better answers about how it all started.

We have dwelt on the question of the origin of the solar system for several reasons. The evolutionary course followed by a planet is set by its initial state. The current state of Earth, some 4.7 billion years later, is reasonably well known to us. These two times in the course of **planetary evolution**—the beginning and now—are important constraints in developing models of how the