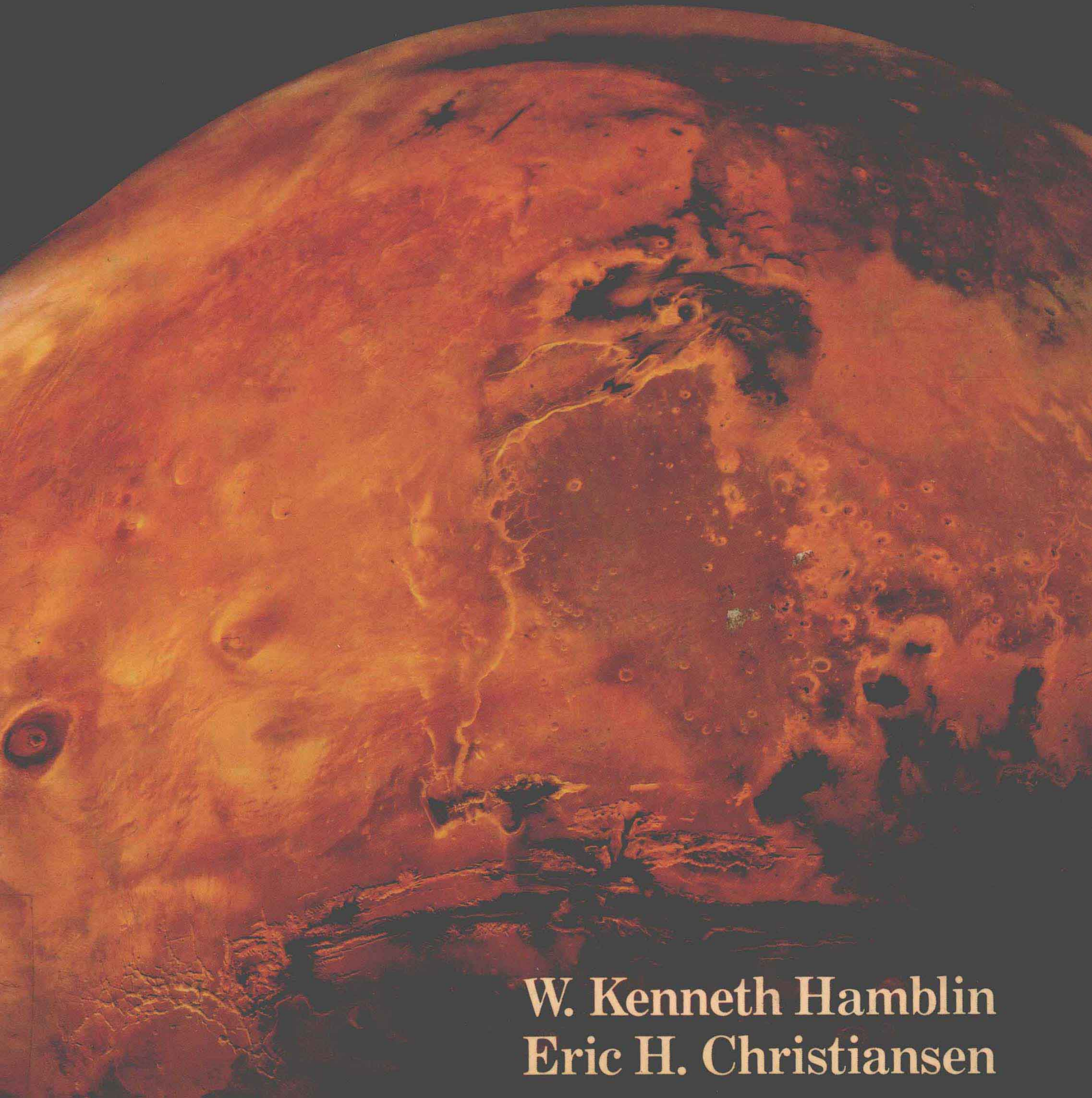
Exploring the Planets



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PREFACE

Endowed with an irrepressible curiosity, the human species has always explored. Humans first explored their immediate surroundings, then neighboring mountains, valleys, and rivers, then adjacent lands, and eventually the vast oceans and faraway continents. Even the night skies were the object of intense scrutiny and wonderment. With time, people would use telescopes to explore the planets more closely. Eventually, the desire to explore using the capabilities of our technology broke the bonds of Earth's gravity and took us to visit, sometimes through remote eyes, our planetary neighbors.

Twenty years ago, we first extended our reach beyond our home planet with a brief visit to the Moon. The exploration of the solar system that followed was just as revolutionary in its way as the exploration of our own planet was in the centuries that preceded this event. In slightly more than two decades we have collected a variety of samples from the surface of the Moon, probed the atmosphere of Venus, mapped the huge volcanoes and canyons of Mars, photographed the surface of Mercury, examined comets close up, and explored the frigid surfaces of the moons of Jupiter, Saturn, Uranus, and Neptune. Of all the planets, only Pluto has not been visited by spacecraft in the past 20 years. There will be other exciting periods of space exploration to be sure, and many great and significant discoveries are waiting to be made, but no other generation will explore for the first time so many worlds in our solar system. Subsequent missions to the planets, among them the *Observer* (to Mars), the *Magellan* (to Venus), the *Galileo* (to Jupiter), the *CRAF-Cassini* (to a comet, the asteroids, and Saturn), and a possible return to the Moon, will provide a flood of data to help us understand the processes that shaped these planetary objects, but the most exciting phase—exploring the surfaces of these bodies for the first time—is over.

It is now an appropriate point to summarize the scientific results of these exploratory missions. We have written this book to share with you some of the knowledge that was gained from this important period of discovery and to introduce you to the study of geology by considering the fundamentals of how planets originate and evolve.

We hope this book will appeal to all who are curious about planets, moons, and other objects in the solar system. Our approach is nonmathematical, but nonetheless analytical; as such, we hope it will be used by a broad range of interested people, even those with little scientific background. The book emphasizes the surfaces, internal structures, and histories of the planets from a geological point of view. We assume only what is typically obtained in high school science classes and the intuition gained by experience with our surroundings. The metric system of measurement is used throughout the book; distances are expressed in meters and kilometers, masses in grams and kilograms, and temperatures in degrees Kelvin.

This book could serve as a text for an introductory college science course or as a supplement to college astronomy or geology courses. The chapters are ordered to provide a logical flow of ideas regarding the development of the planets. After considering some of the fundamental principles needed to understand the planets, we proceed from small, simple bodies like the Moon to larger, more complex bodies like Earth and Venus. The asteroids are discussed next as parent bodies to meteorites and in their role as building blocks of the inner planets. The outer planets are discussed in the order of occurrence outward from the Sun. Comets are discussed as the icy parent bodies of the outer planets. A closing chapter compares the planets by briefly examining the principal processes that have shaped the planets. Although Chapters 1 and 2 would be most helpful if studied first, the other chapters generally contain enough background material to stand alone or to be read out of sequence. Thought-provoking questions and additional reading are listed at the end of each chapter for those who wish to explore further on their own.

Acknowledgments

We sincerely thank all those that have made the exploration of the planets possible—principally, the citizens of the United States and the Soviet Union. Through their desire to know and understand their surroundings, the people of these countries have appropriated funds to construct rockets, spacecraft, and sophisticated instruments that have endowed us with the remote vision we require to explore the planets.

We are also grateful to the following colleagues who reviewed the entire text or various chapters and offered many helpful suggestions: C. J. Casella, Northern Illinois University; Ronald Greeley, Arizona State University; James W. Head III, Brown University; R. Craig Kochel, Southern Illinois University, Carbondale; Jeffrey Moore, Arizona State University; Carleton Moore, Arizona State University; Quinn Passey, Exxon Research; Steven Croft, University of Arizona; Joseph Veverka, Cornell University.

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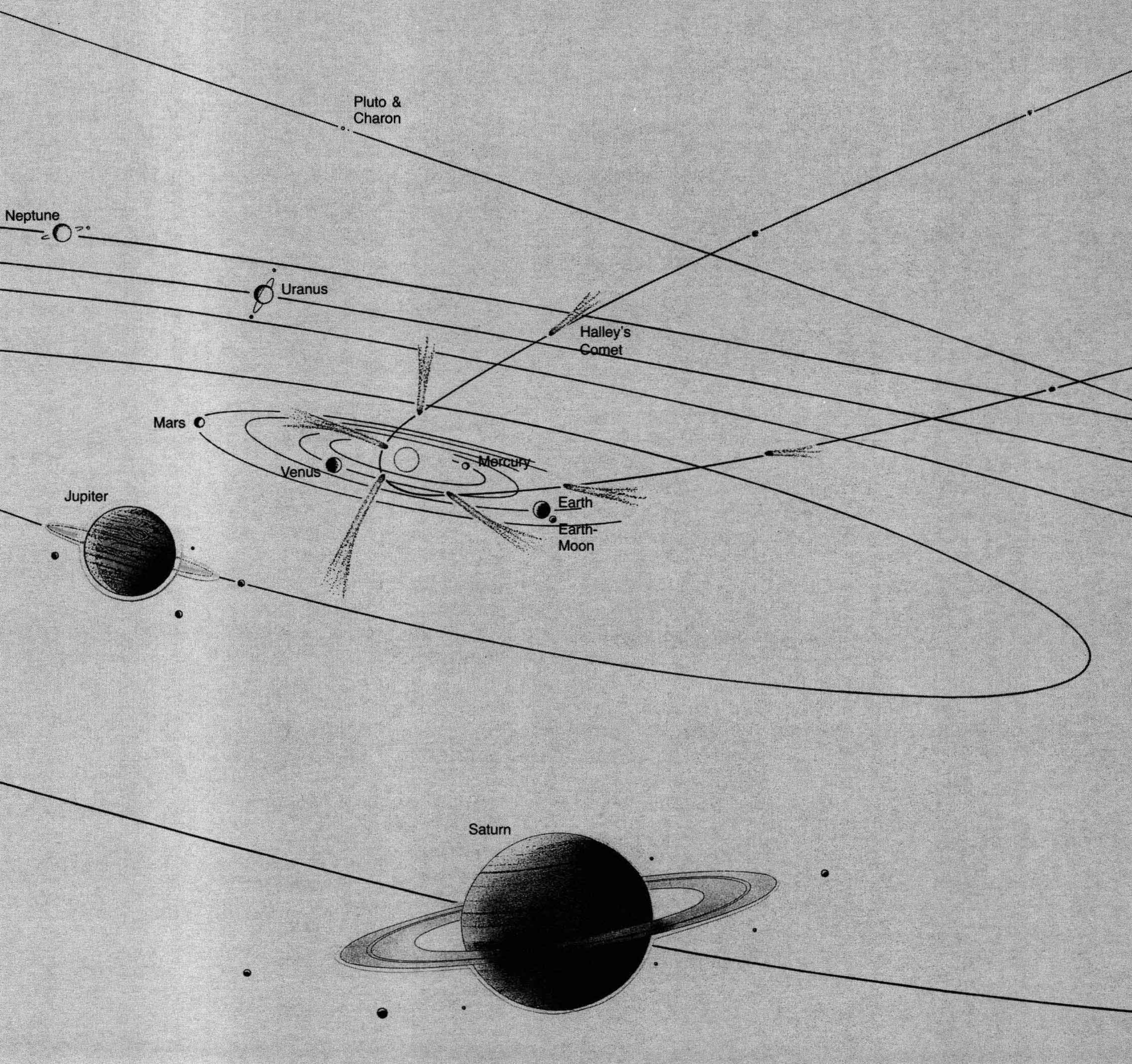
CHAPTER 1

The Solar System



Introduction

Our solar system consists of one star, a family of nine planets, at least 58 moons, thousands of asteroids, and billions of meteoroids and comets. In terms of mass however, the solar system consists of very little else than the Sun itself. This ball of gas comprises 99.87 percent of the mass of the solar system and most of the remaining 0.13 percent resides in Jupiter. Thus most of the solar system is empty space. From the nearest star, using technology currently available on Earth, nothing could be seen of our solar system except the Sun, and it would appear only as a small yellowish star of a type common in the galaxy. Nonetheless, the planetary objects that orbit the Sun are extremely important, and our new knowledge about them is changing the way we look at the solar system and Earth itself.

In the annals of history, the second half of the twentieth century may well be remembered more for the exploration of the planets than any other single achievement of mankind. No other generation has had the opportunity to reach beyond our own world and see, touch, and hear the forces that shape our universe. Thus, our objective in this chapter is to introduce you to the results of this vast undertaking by making a brief survey of the nature of the major planetary objects.

Major Concepts

1. A planet is a body, not large enough to generate nuclear fusion reactions, that orbits a star. Planets are composed of metals, silicates, ices, and gases.
2. The solar system contains nine planets and 24 other planetary bodies (moons and asteroids) with diameters greater than about 400 kilometers. Some icy comets in the far reaches of the solar system may also be this large.
3. The small inner planets (Mercury, Venus, Earth, and Mars) are composed mostly of silicate rocks and metals; the outer planets (Jupiter, Saturn, Uranus, and Neptune) are much larger, consist mostly of hydrogen, helium, and ice, and have large systems of icy moons. Pluto, the smallest planet in the solar system, is similar to the moons of the outer planets in size and composition.
4. The asteroids, fragments of once larger rocky bodies, orbit the Sun and are concentrated between the orbits of Mars and Jupiter.
5. Comets are small icy bodies formed in the outer solar system. If their orbits become changed they may enter the inner solar system for a short time.
6. The surface features, compositions, interior structures, and other characteristics of planetary bodies are records of the events which shaped them. The distinctions between planets, moons, asteroids, and comets are largely arbitrary. Each world has a story to tell us about its development, adding to our understanding of how matter and energy interact in our solar system.

Planets, Moons, Asteroids, and Comets

By tradition it has generally been assumed that there is a clear-cut distinction in the hierarchy of planets, moons, asteroids, and interplanetary debris (planets being the larger objects, moons being smaller and orbiting a planet, etc.). As a result of the space program we are obliged to look at the solar system differently. The solar system is really made up of 26 worlds larger than 1000 km in diameter; worlds that record a variety of events in planetary evolution and shed spectacular new light on the origin and history of our own planet, Earth. The traditional practice of classifying objects in the solar system as planets, moons, asteroids, comets, or meteorites establishes artificial categories that may blur important similarities.

Planets are objects that orbit (or revolve) around a central luminous star (Figure 1.1). Our Sun is a medium-sized star, only one of about 100 billion stars that collectively form a slowly rotating spiral galaxy (Figure 1.2). Planets are commonly solid, but liquids and gases are also important constituents. Planets are too small for nuclear fusion reactions to have initiated within their interiors. The principal planets in order outward from the Sun are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. **A planetary body** is a general term referring to any body orbiting a star. Planetary bodies include planets and their natural satellites or moons, as well as smaller objects such as asteroids and comets. They range in size from the small asteroids to the largest of the planets.

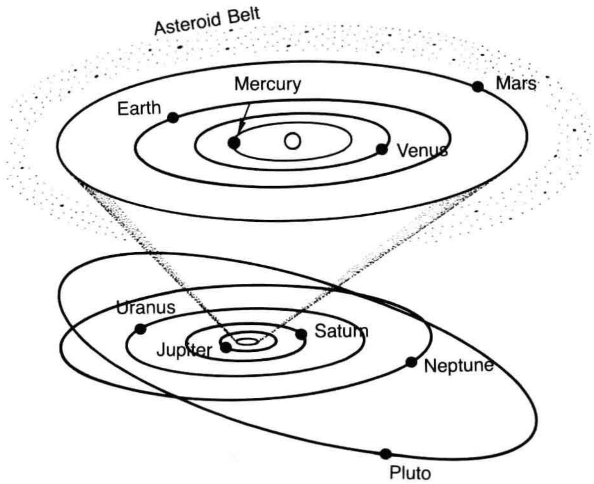


Figure 1.1
The orbits of the principal planets of the solar system are centered on the Sun—a medium-sized star. All of the planets, except Pluto, revolve about the Sun near the equatorial plane of the solar system. Pluto's elliptical orbit is tilted by over 17 degrees. Viewed from above the solar system, all the planets move in normal counterclockwise directions. The necessity of enlarging the inner solar system emphasizes the scale problem encountered in such a display. If Pluto's path were about the size of a bicycle tire, the orbits of the four inner planets would fit inside a circle smaller than a quarter. In addition to the planets, there are at least 44 moons, thousands of small rocky asteroids, and billions of icy comets. The location of the asteroid belt, where most asteroids occur, is shown between the orbits of Jupiter and Mars.

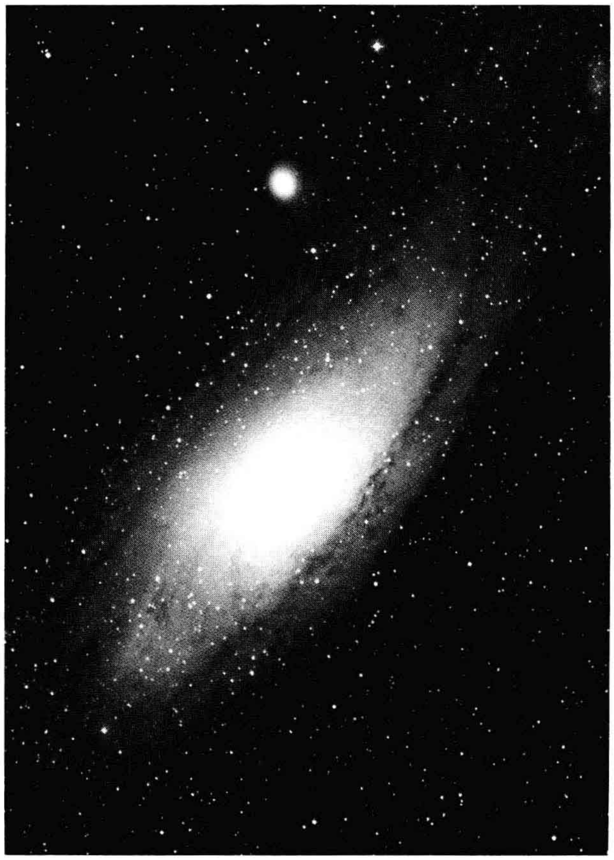


Figure 1.2
A galaxy, like the one shown here, is a grouping of billions of stars. The Sun and the planets are part of the Milky Way galaxy, which is probably similar to this spiral galaxy. Located in one of the arms, our solar system revolves about the center of the galaxy at a speed of over 200 km per second. Yet the galaxy is so vast that it takes about 250 million years to complete one revolution. The Sun has yet to complete its nineteenth orbit about the galactic center.

The relative sizes of the major planetary bodies in the solar system are shown in Figure 1.3. Descriptive information about the planetary objects discussed in this book is listed in the table at the beginning of this Chapter; it is most useful for comparative purposes. The **inner planets** (Mercury, Venus, Earth, and Mars) are also called the **terrestrial** planets (Earthlike). They are relatively small worlds composed of silicate (silicon-oxygen compounds) rock surrounding metallic cores. Farther from the Sun lie the four gas giants, with deep atmospheres that thicken downward into hot liquid, probably surrounding small, solid rocky or icy cores. These planets have no solid surfaces. Jupiter, Saturn, Uranus, and Neptune all have rings of small particles that encircle them. The outermost planet is Pluto, which is smaller than even Mercury. Natural satellites, or moons, orbit every planet except Mercury and Venus. The satellites of Earth and Mars are composed of silicate rock. Jupiter has a miniature planetary system comprised of four large moons and at least 12 smaller ones. The larger moons have rocky cores, which are covered with thick mantles of ice. Saturn is also the center of a miniature planetary system, involving more than 17 planetary bodies. The moons of Saturn and Uranus are relatively small icy bodies (except for Titan) with possible small rocky cores. Little geologic information is known about the moon of Pluto, but it may resemble the icy satellites of Uranus and Neptune.

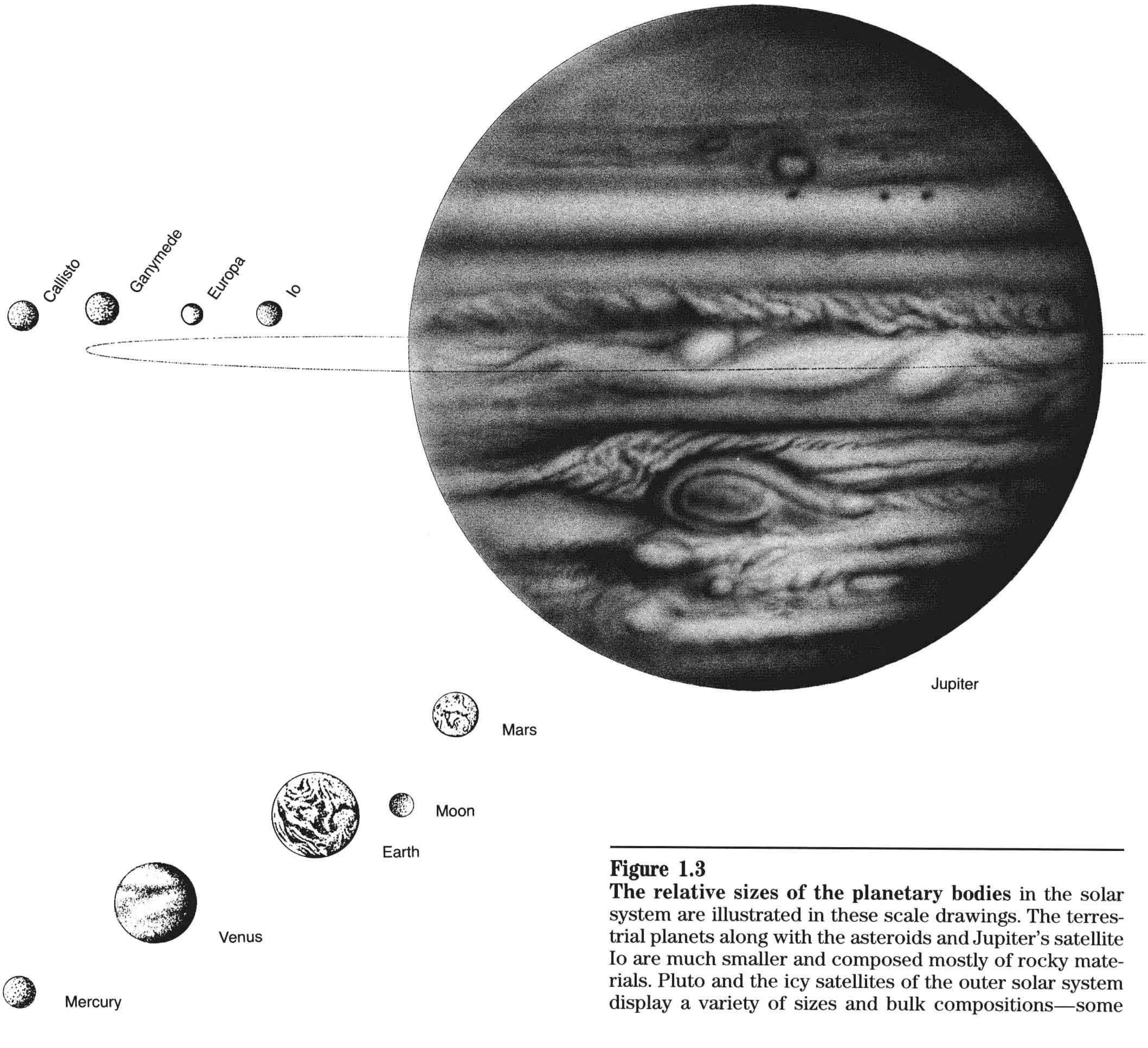
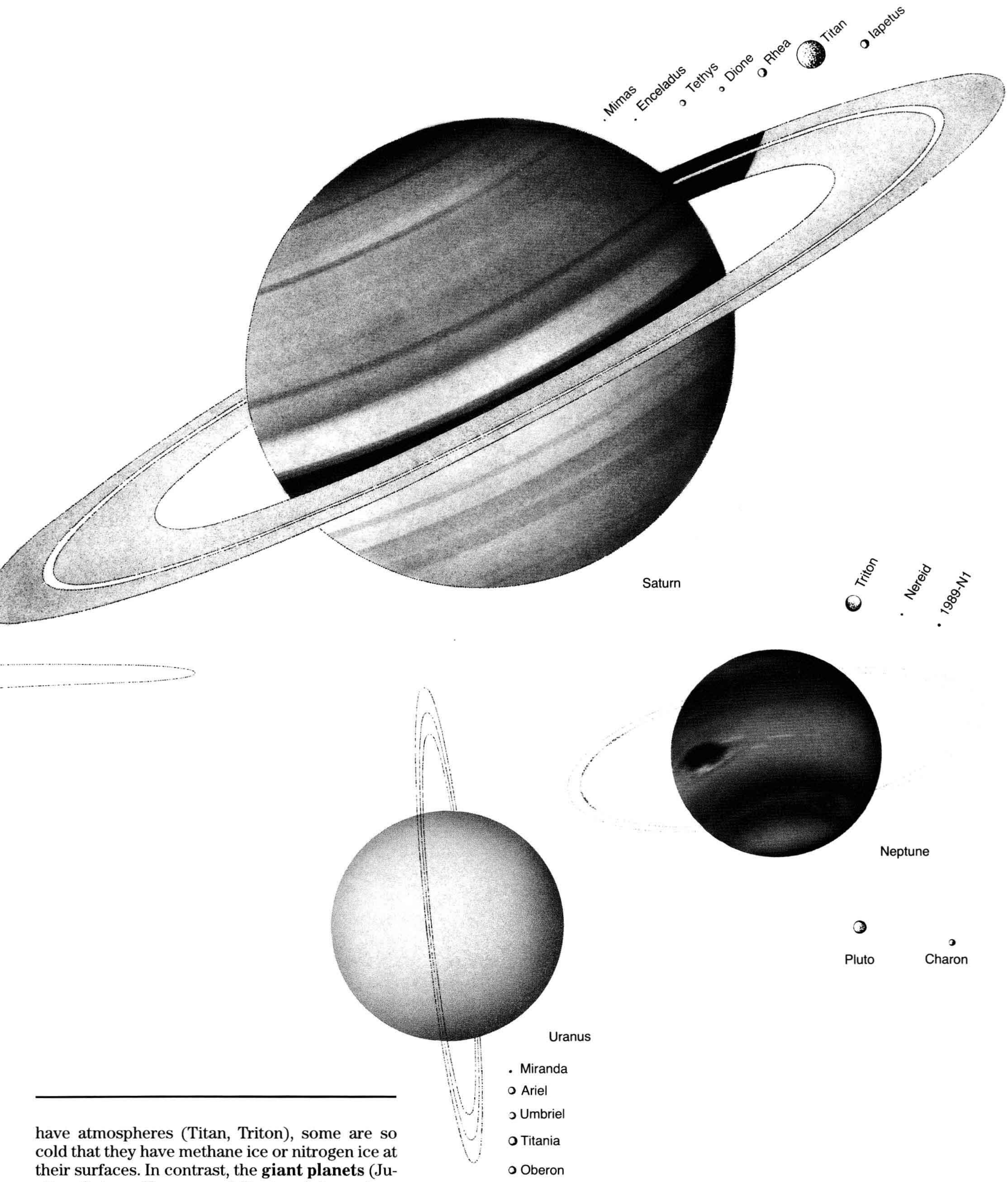


Figure 1.3
The relative sizes of the planetary bodies in the solar system are illustrated in these scale drawings. The terrestrial planets along with the asteroids and Jupiter's satellite Io are much smaller and composed mostly of rocky materials. Pluto and the icy satellites of the outer solar system display a variety of sizes and bulk compositions—some



have atmospheres (Titan, Triton), some are so cold that they have methane ice or nitrogen ice at their surfaces. In contrast, the **giant planets** (Jupiter, Saturn, Uranus, and Neptune) have deep atmospheres of hydrogen and helium and no solid surfaces.

Mercury

Mercury is the innermost planet (Figure 1.4). It orbits the Sun at only 40 percent of the distance the Earth lies from the Sun. Spacecraft observations of Mercury were made on three occasions in 1974 and 1975, when Mariner 10 photographed approximately half of the planet. With no atmosphere to moderate its environment, the temperature range at the surface is extreme, from 90 K on the surface turned away from the Sun to about 740 K on the surface facing the Sun. No clouds hide Mercury's surface, which is dominated by circular craters formed when large meteorites struck it. Many of the craters are between 3 and 4 billion years old. The largest impact crater shown here is almost 1300 km across. Broad patches of smooth plains, deformed by a system of wrinkles, occur between the craters. The plains may have been produced when the interior warmed and partially melted to produce lavas, which were then extruded onto the surface. Mercury appears to be composed of rocky materials similar to the other inner or **terrestrial planets**. A magnetic field and a high bulk density for Mercury hint at the presence of an iron-rich interior that may still be molten.

Venus

Nearly two and a half times larger than Mercury and farther from the Sun, **Venus** stands in striking visual contrast to Mercury (Figure 1.4). Its orbit is closer to a perfect circle than any of the planets, yet it moves in odd ways. Its rotation is retrograde or backward and its spin is so slow that four Earth months go by during the time Venus spins once on its axis. In addition, Venus orbits the Sun in less than two of its days. The surface of Venus is totally obscured by a thick atmosphere composed mostly of carbon dioxide with sulfuric acid clouds (Figure 1.4). Nonetheless, Soviet and American spacecraft using radar instruments have revealed an outline of the planet's most important surface features. Mountain belts, volcanoes, and two high "continents" rise several kilometers above vast rolling plains—a surface similar in some ways to Earth with its continents and ocean basins. However, Venus has almost no water and temperatures at its surface (almost 750 K) are higher than on Mercury.

Earth

Earth, the third planet from the Sun, is dominated by the waters of its ocean and the white swirling patterns of clouds, underlining the importance of the atmosphere and of water for the development of the surface features of Earth. Several complete cyclonic storms, spiraling over hundreds of square kilometers, are illustrated in Figure 1.4. They pump huge quantities of water from the ocean to the atmosphere. Much of this water is precipitated on the continents and erodes the land as it flows back to the sea. Earth's poles are marked by ice caps—the Antarctic continent, shown here, is covered by a polar ice cap which is 3 km deep in places. Huge oceans of liquid water cover 70 percent of the planet.

Rising above the oceans, Earth's continental highlands are etched by delicate systems of river valleys. In this view, large parts of the continental highlands of Africa and Antarctica are also visible above the level of the sea. In striking contrast to some of the other inner planets, no large impact basins are visible from this distance. Indeed, such structures are rare on Earth, and most of its rocks are less than 2.5 billion years old. Its landforms are extremely young, shaped by the relentless flow of water and wind. Of particular interest in this view is the rift system of the Red Sea, a large growing fracture in the African continent that separates Arabia from Africa. This fracture attests to the mobility of Earth's **lithosphere**, its outer solid layer. The lithosphere is fragmented, and each segment moves slowly about the planet. Active volcanoes and earthquakes still produce dramatic changes at the surface.

Self-replicating molecules of carbon, hydrogen, nitrogen, and oxygen—life—developed early in Earth's history; they have substantially modified the planet's surface, blanketing huge parts of the continents with greenery. Tropical jungles create the dark band across equatorial Africa, dramatic evidence of the unique chemistry of Earth. Life thrives on this planet, which has an oxygen and nitrogen-rich atmosphere and moderate temperatures (generally above 275 K). Perhaps if nothing more, our studies of the diversity of compositions and conditions of solar system bodies should remind us of the delicate balance of energy, environment, and evolution which allows us to exist at all.

The Moon. With the developments of the space program the Moon has become one of the best-understood planetary bodies in the solar system. As curious as it may seem, less than two decades after putting astronauts on the Moon, we probably understand the earliest history of the Moon better than that of Earth, for Earth lacks a rock record of its first 800 million years of history. The surface of the Moon (Figure 1.4) shows two contrasting types of landforms, which reflect two major periods in its history. The bright, densely cratered highlands are similar to the surface of Mercury. Most of the large impact craters formed before about 4 billion years ago. The dark, smooth areas are called maria and most occupy

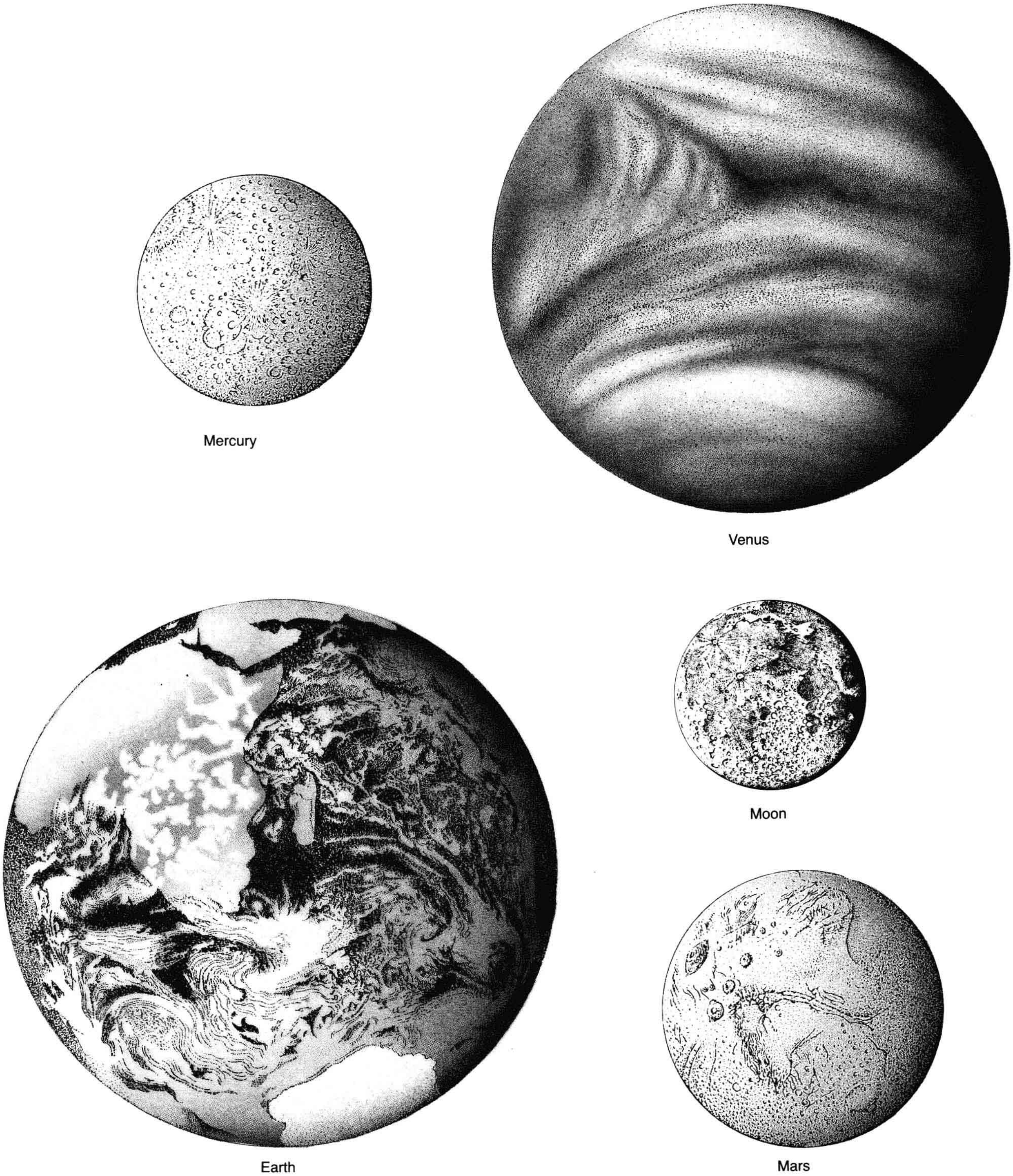


Figure 1.4
The surfaces of the inner planets (Mercury, Venus, Earth, the Moon, and Mars) drawn to a common scale reveal the diversity found in the solar system. Mercury, the Moon, and Mars have many craters formed when meteorites collided with their surfaces billions of years ago. Venus and Earth have conspicuous atmospheres and surfaces that are relatively young.

low regions, such as the circular interiors of impact basins. We know from rock samples brought back from the Apollo missions that the maria resulted from great floods of lava, which filled many large craters and spread out over the surrounding area. The volcanic activity therefore occurred after the formation of the densely cratered terrain. Radiometric dates on samples brought back from the Moon indicate that most of the lavas are over 3 billion years old. However, some young impact craters with bright rays formed after these eruptions. Like Mercury, the Moon is a dry airless world. The lunar surface has not been modified by wind, water, or glaciers, but its surface features record major events early in the history of the solar system, when impact of meteorites was the major geologic process throughout the solar system.

Mars

Mars, the red planet, is smaller and less dense than the Earth. For years it was considered to be a planet of mystery because telescopic observations revealed polar ice caps and shifting markings, which often darkened during the martian spring. Some thought that Mars was populated and that life forms had evolved to a civilized state. Streaks were believed to be canals or vegetated land alongside canals. As it turns out, these fanciful theories were all wrong, but in a different way Mars is just as fascinating. Unlike the Moon, many features of Mars indicate that its surface has been modified by atmospheric processes, running water, recent volcanic activity, and lithospheric deformation. Its surface is divided into two distinctly different hemispheres (Figure 1.4). The northern hemisphere has few meteorite impact craters and consists of vast, relatively smooth plains. The southern hemisphere, in contrast, is higher and moderately to heavily cratered. A broad fractured swell capped by several great volcanoes overlaps the boundary between the hemispheres. Huge channels, apparently carved by running water, course across the surface of Mars. Liquid water cannot exist at its surface today, yet Mars has had abundant liquid water on its surface in the past. What happened? The question will be debated for years but one thing seems certain: Mars has experienced significant changes during its history—changes recorded on its surface and in its landscapes, changes that are still occurring—as evidenced by planetwide dust storms, wind-blown sand, tenuous mists, and clouds.

The Asteroid Belt

Occupying the vast tract between Mars and Jupiter is the **asteroid belt** (Figure 1.5). It consists of thousands of small bodies ranging from less than 1 to just over 1000 km in diameter. The asteroids mark the transition from the rocky terrestrial planets to the gas- and ice-rich outer planets. Some asteroids appear to be rocky, some seem covered with lavas, others seem to be metallic, and yet others may have water ice.

Many **meteorites** are derived from the asteroids. **Meteorites** are small planetary bodies composed of iron or silicate rock that reach the Earth from space. Called **meteoroids** before they hit a planet, they are actually fragments of asteroids or comets (and more rarely of moons or planets). These pieces of planetary material are extremely valuable because they provide scientists with tangible samples of planetary bodies that can be analyzed in great detail. Moreover, expensive spacecraft are not necessary to obtain them.

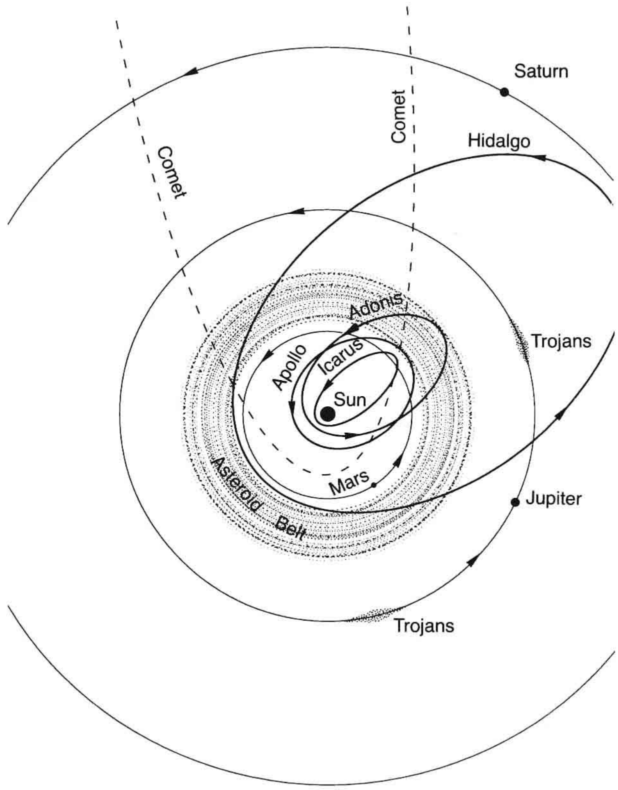


Figure 1.5
The asteroid belt lies between the orbits of Mars and Jupiter and is occupied by thousands of small rocky bodies in orbit about the Sun. The largest asteroids are Ceres, 1000 km in diameter, and Vesta, 550 km in diameter. Vesta may be covered by lava flows. These bodies are indeed small planets. The orbits of many asteroids lie outside of the main belt, and these may be the sources of some of the meteorites which fall to the Earth.

Jupiter

Jupiter is the largest planet in the solar system; in fact, most of the mass of the solar system outside of the Sun is in Jupiter. Jupiter has no solid surface. The spots and colorful bands (Figure 1.6) that parallel its equator are the turbulent manifestations of motion in a thick, cloudy atmosphere of hydrogen and helium. Jupiter and the other outer planets have compositions dramatically different from the rocky inner planets. In addition, Jupiter is the center of a miniature planetary system and a narrow ring. It has four large moons, which are called the **Galilean satellites**, because they were discovered by Galileo. Each of these moons is larger than Pluto and each presents diverse surface features resulting from meteorite impact, volcanism, and surface fracturing. Like the principal planets, these satellites show significant compositional changes outward from their primary.

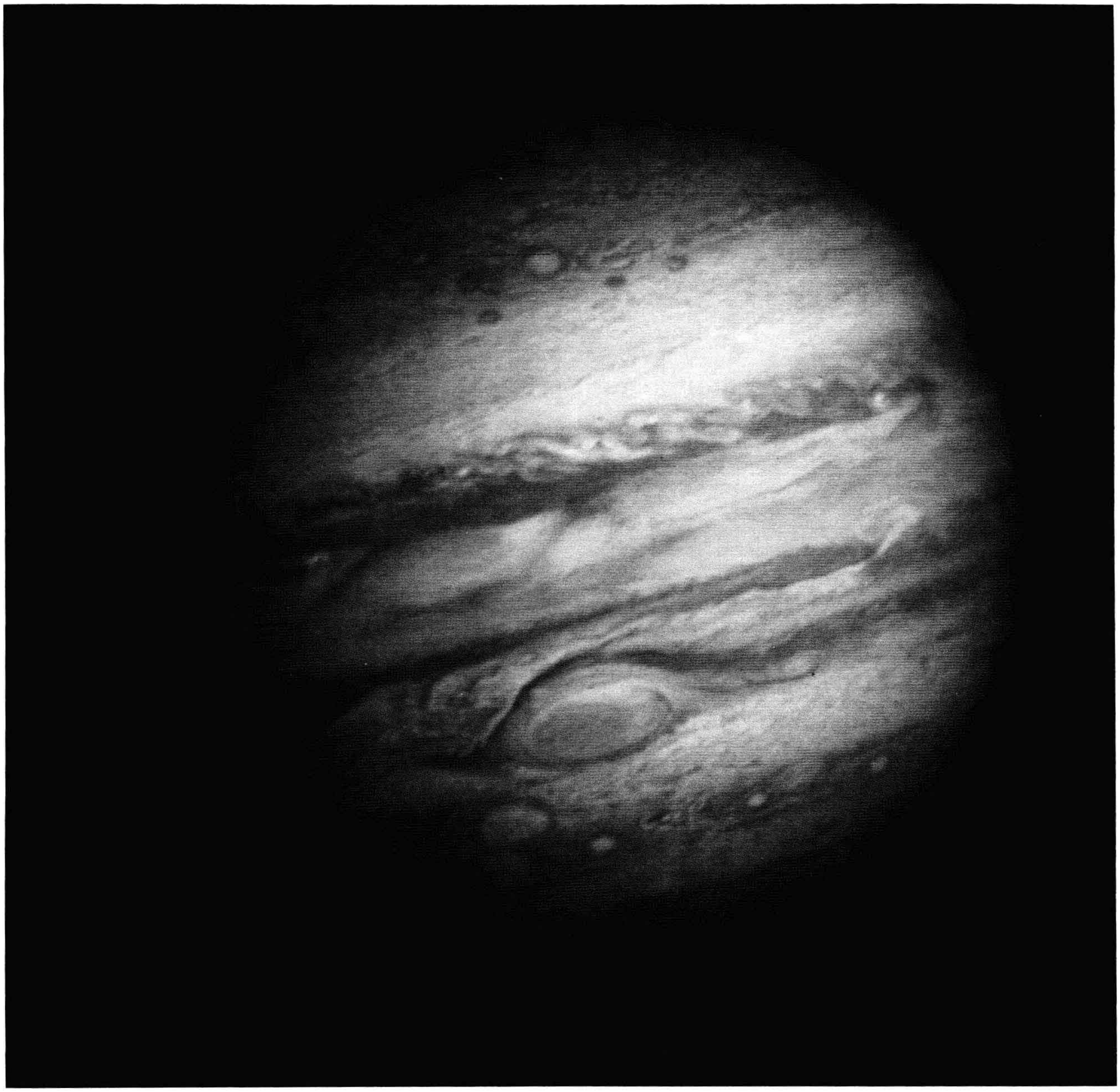


Figure 1.6
Jupiter is the largest and most massive planetary body in the solar system. Its banded appearance is the result of circulation in an extremely thick atmosphere of hydrogen and helium, and details of the bands are constantly changing. The clouds come in a variety of subtle hues of red, yellow, brown, and white. The large oval structure, the Giant Red Spot, in Jupiter's southern hemisphere is a cyclonic storm larger in diameter than the Earth itself.