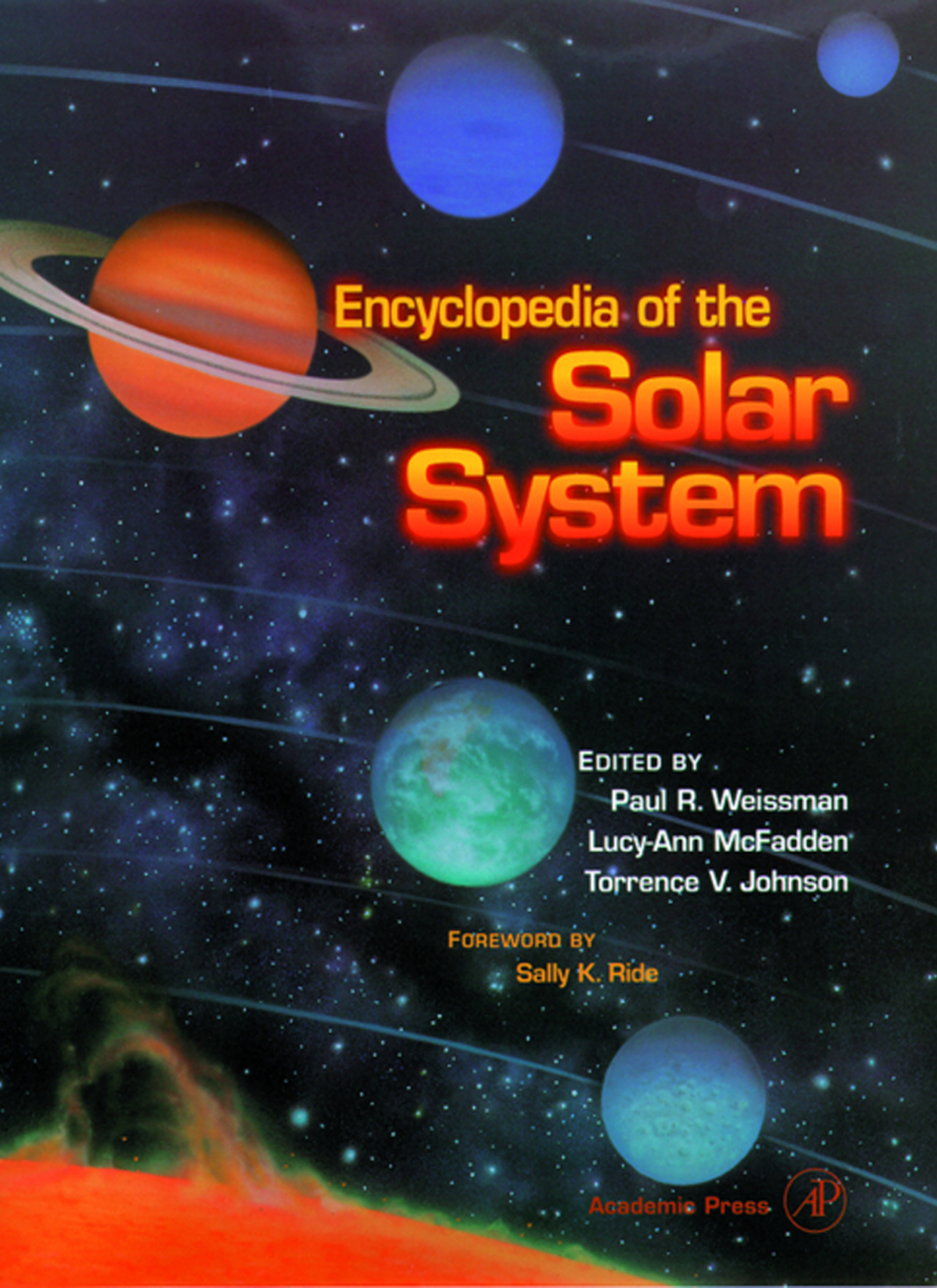
Encyclopedia of the
Solar
System
Edited by
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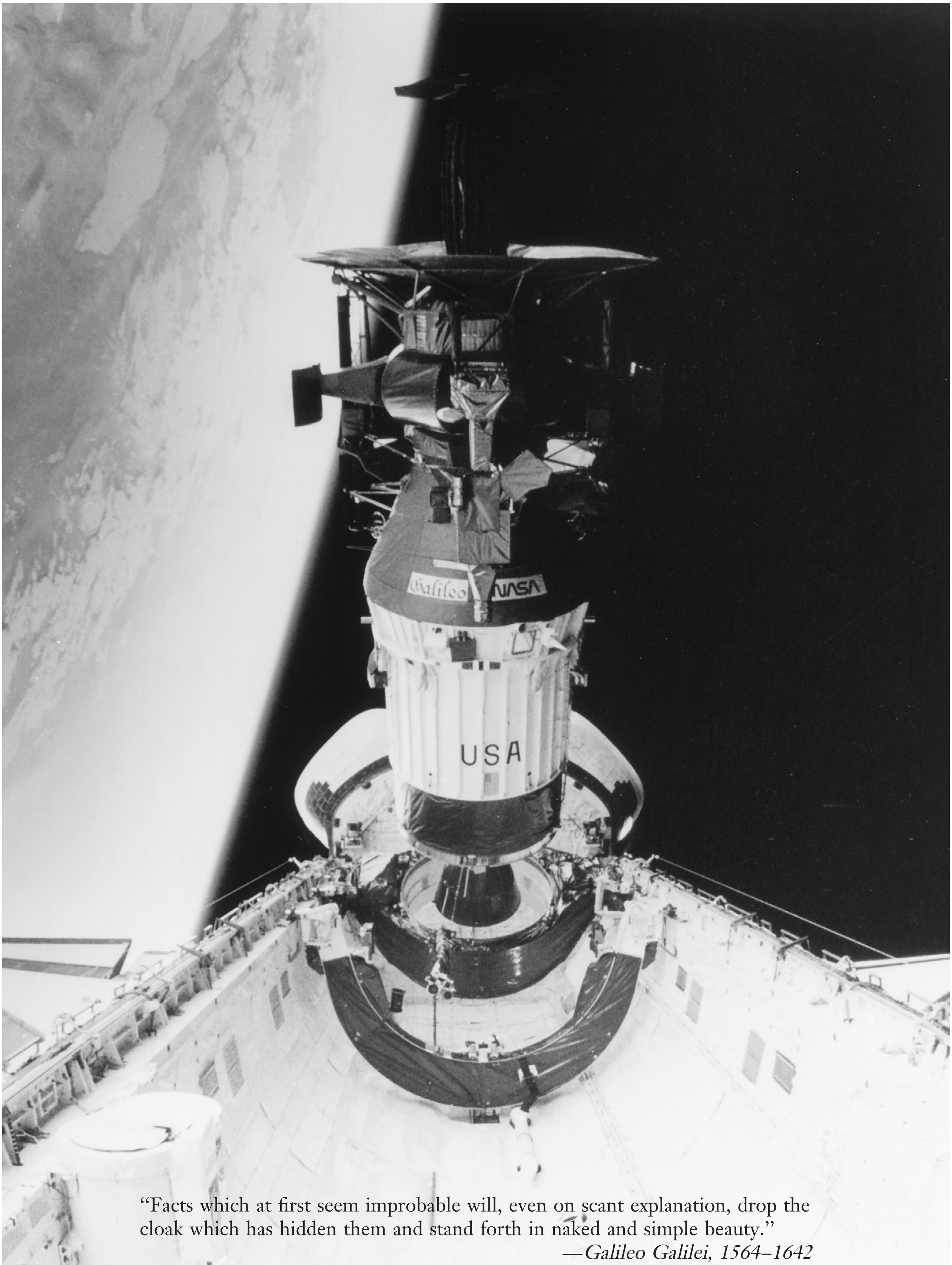
ENCYCLOPEDIA of the SOLAR SYSTEM



"Facts which at first seem improbable will, even on scant explanation, drop the cloak which has hidden them and stand forth in naked and simple beauty."

—Galileo Galilei, 1564–1642

ENCYCLOPEDIA of the SOLAR SYSTEM

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Jacket: An artist's view of the Solar System as observed from the Sun. Painting by Brad Greenwood.

Frontispiece: Launch of the Galileo spacecraft from the shuttle Atlantis, October 18, 1989. Galileo used gravity-assist flybys of Venus and the Earth to get to Jupiter, where it went into orbit on December 7, 1995. (NASA photo; courtesy of IMAX Corporation.)

Appendix: Launch of the Cassini Orbiter and Huygens Probe on Titan IV. (NASA photo)

Website: Academic Press maintains a WWW site for the Encyclopedia at *www.academicpress.com/solar/*. Author-recommended web resources for additional information, images, and research developments related to each chapter of this volume are available here.

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FOREWORD

None of the other worlds in our solar system look like Earth.

When I was orbiting our planet in the Space Shuttle, I would often float over to a window and gaze down at the sparkling blue oceans, billowing white clouds, and rugged mountaintops of the Earth below. The signs of life are everywhere. A patchwork of fertile farmland lines the lazy Mississippi River, vast blooms of phytoplankton color the coastal waters of Southern Africa, and glittering coral reefs circle the islands of the Caribbean. At night, Earth's continents are outlined by twinkling city lights. Our planet is truly an oasis in space.

The view from space shows us how different Earth is from the other planets, but it also shows that many of the same processes that shape other worlds—wind and weather, impacts and volcanism—shape our planet, too. Through the Shuttle window, I watched an enormous dust storm grow until it blotted out all of Northern Africa. I saw the eroded remnants of an ancient impact crater in Eastern Canada, looked along a chain of volcanic islands in the Pacific Ocean, and gazed into a gaping rift valley in East Africa.

Imagine what it would be like to orbit an alien world: to watch a giant dust storm sweep across the ancient highlands of Mars, or look down on the slumping impact craters of Callisto, or see the gushing ice geysers of Triton. What would it be like to swing past Titan with Voyager 1, ride with Giotto past the icy heart of Halley's Comet, or wander with Sojourner across an ancient Martian floodplain? Though astronauts have never traveled beyond our own moon, humankind can now see the magnificent rings of Saturn, the tortured surface of Io, and the stormy atmosphere of Neptune through the eyes of robotic spacecraft.

Before the dawn of the Space Age, our instruments were confined to Earth's surface. Telescopes strained to gather light from worlds that were hundreds of millions of miles away. Even the most powerful produced fuzzy images of the planets, and only whetted scientists' appetites for more detailed observations. Then, in 1957 the Soviet Union launched the world's first satellite into orbit around Earth. Sputnik rocketed the world into the Space Age, and ignited a race between the United States and the Soviet Union for space superiority, the most public aspect of which was the race to the Moon. These new technical capabilities also stimulated the robotic exploration of our solar system, exploration that would continue long after Neil Armstrong left his bootprints in the lunar soil.

Today, spacecraft have visited every planet except Pluto. The Ulysses spacecraft circled above the poles of the Sun; Venera plunged headlong into the crushing carbon dioxide atmosphere of Venus; Vikings scooped up soil from the dusty red surface of Mars; and Galileo photographed barren, battered asteroids during its long journey to Jupiter. As these robot explorers radioed images and data back to Earth, they changed our view of the solar system forever.

The Encyclopedia of the Solar System appears at a propitious time. Not since 1609, when Galileo first turned his telescope to the heavens, has there been such a revolutionary change in our view of the solar system. Its pages are bursting with the knowledge gained as a result of data gathered by this fleet of robotic spacecraft and by a new generation of space- and ground-based telescopes. It takes us back 4.6 billion years to the origin of the solar system, then leads us on a tour that extends from the fiery interior of the Sun to the icy comets of the Kuiper Belt. It describes forces ranging from the solar wind that streams through all of interplanetary space, to the colossal impacts that affect every world.

Closer to home, this Encyclopedia makes it clear that our new perspective from space has revolutionized our understanding of Earth. Importantly, it also describes our continuing search for the answer to one of our most fundamental questions: Is life unique to our planet, or will it develop wherever conditions are right? Scientists are now asking whether primitive life might have begun in the hydrothermal vents of ancient Mars, or in the churning seas beneath the ice-covered surface of Europa. Our exploration is teaching us about Earth's origins and evolution; it may also teach us something about the origin of life itself.

Carl Sagan often pointed out how lucky we are to live at the very moment in human history when men and women are taking their first steps off the Earth. Every day for the last several years, astronauts have been living in Earth orbit; every day, orbiting telescopes have been sending us images unobscured by Earth's atmosphere; and every day, distant spacecraft have been sending us information from faraway worlds. In this remarkable era of exploration, we are literally discovering new things about the universe every day.

The scientists whose work is described in this Encyclopedia have dedicated their careers to exploring the unknown. Their curiosity has led them to pose questions, propose theories, and conduct observations to help unravel mysteries that have intrigued scientists for centuries. This volume collects the contributions of the authors and, through them, hundreds of other scientists around the world. It represents our current state of knowledge on the origin, the evolution, and the fascinating components of our solar system. I invite you to join these scientists on their breathtaking journey. As you read their words, I encourage you to imagine, wonder, and question, just as they have.

Reach for the stars!

Sally K. Ride

PREFACE

"This is what hydrogen atoms can accomplish after four billion years of evolution."
—Carl Sagan, Cosmos, 1981

The quote above comes from the final episode of the public television series "Cosmos," which was created by Carl Sagan and several colleagues in 1981. Carl was describing the incredible accomplishments of the scientists and engineers who made the Voyager 1 and 2 missions to Jupiter and Saturn possible. But he just as easily could have been describing the chapters in this book.

This Encyclopedia is the product of the many scientists, engineers, technicians, and managers who produced the spacecraft missions which have explored our solar system over the past four decades. It is our attempt to provide to you, the reader, a comprehensive view of all we have learned in that 40 years of exploration and discovery. But we cannot take credit for this work. It is the product of the efforts of thousands of very talented and hard-working individuals in a score of countries who have contributed to that exploration. And it includes not only those involved directly in space missions, but also the many ground-based telescopic observers (both professional and amateur), laboratory scientists, theorists, and computer specialists who have contributed to creating that body of knowledge called solar system science. To all of these individuals, we say thank you.

Our goal in creating this Encyclopedia is to provide an integrated view of all we have learned about the solar system, at a level that is useful to the advanced amateur or student, to teachers, to non-solar system astronomers, and to professionals in other scientific and technical fields. What we present here is an introduction to the many different specialties that constitute solar system science, written by the world's leading experts in each field. A reader can start at the beginning and follow the course we have laid out, or delve into the volume at almost any point and pursue his or her own personal interests. If the reader wishes to go further, the lists of recommended reading at the end of each article provide the next step in learning about any of the subjects covered.

Our approach is to have the reader understand the solar system not only as a collection of individual and distinct bodies, but also as an integrated, interacting system, shaped by its initial conditions and by a variety of physical and chemical processes. The Encyclopedia begins with an overview chapter which describes the general features of the solar system and its relationship to the Milky Way galaxy, followed by a chapter on the origin of the system. Next we proceed from the Sun outward. We present the terrestrial planets (Mercury, Venus, Earth, Mars) individually with separate chapters on their atmospheres and satellites (where they exist). For the giant planets (Jupiter, Saturn, Uranus, Neptune) our focus shifts to common areas of scientific knowledge: atmospheres, interiors, satellites, rings, and magnetospheres. In addition, we have singled out three amazing satellites for individual chapters: Io, Titan, and Triton. Next is a chapter on the planetary system's most distant outpost, Pluto, and its icy satellite, Charon. From there we move into discussing the small bodies of the solar system: comets, asteroids, meteorites, and dust. Having looked at the individual members of the solar system, we next describe the different view of those members at a variety of wavelengths outside the normal visual region. From there we consider the important processes that have played such an important role in the formation and evolution of the system: celestial dynamics, chaos, impacts, and volcanism. Last, we look at three topics which are as much in our future as in our past: life on other planets, space exploration missions, and the search for planets around other stars.

A volume like this one does not come into being without the efforts of a great number of very dedicated people. We express our appreciation to the more than 50 colleagues who wrote chapters, sharing their expertise with you, the reader. In addition to providing chapters that captured the excitement of their individual fields, the authors have endured revisions, rewrites, endless questions, and unforeseen delays. For all of these we offer our humble apologies. To ensure the quality and accuracy of each contribution, at least two independent reviewers critiqued each chapter. The peer review process maintains its integrity through the anonymity of the reviewers. Although we cannot acknowledge them by name, we thank all the reviewers for their time and their conscientious efforts.

We are also deeply indebted to the team at Academic Press. Our executive editor, Frank Cynar, worked tirelessly with us to conceptualize and execute the encyclopedia, while allowing us to maintain the highest intellectual and scientific standards. We thank him for his patience and for his perseverance in seeing this volume through to completion. Frank's assistants, Daniela Dell'Orco, Della Grayson, Linda McAleer, Cathleen Ryan, and Suzanne Walters, kept the entire process moving and attended to the myriad of details and questions that arise with such a large and complex volume. Advice and valuable guidance came from Academic Press' director of major reference works, Chris Morris. Lori Asbury masterfully oversaw the production and copy editing. To all of the people at Academic Press, we give our sincere thanks.

Knowledge is not static. Science is a process, not a product. Some of what is presented in this volume will inevitably be out of date by the time you read it. New discoveries seem to come every day from our colleagues using Earth-based and orbiting telescopes, and from the flotilla of new small spacecraft that are out there adding to our store of knowledge about the solar system. In this spirit we hope that you, the reader, will benefit from the knowledge and understanding compiled in the following pages. The new millennium will surely add to the legacy presented herein, and we will all be the better for it. Enjoy, wonder, and keep watching the sky.

Paul R. Weissman
Lucy-Ann McFadden
Torrence V. Johnson

GUIDE TO THE ENCYCLOPEDIA

The *Encyclopedia of the Solar System* is a complete reference guide to this subject, including studies of the Sun, the Earth and the eight other major planets, the Moon and other natural satellites, planetary rings, comets, asteroids, meteorites, and interplanetary dust. Other entries discuss topics such as the dynamics of the solar system and planetary exploration missions. Each chapter in the Encyclopedia provides a scholarly overview of the selected topic to inform a broad spectrum of readers, from researchers to the interested general public.

In order that you, the reader, will derive the maximum benefit from the *Encyclopedia of the Solar System,* we have provided this Guide. It explains how the book is organized and how information can be located.

ORGANIZATION

The *Encyclopedia of the Solar System* is organized in a highly functional manner. It consists of 40 individual chapters that progress in sequence according to the physical arrangement of the solar system itself. That is, the encyclopedia begins with a summary chapter on the entire solar system, then follows with an chapter on the Sun, then the Solar Wind, then Mercury, Venus, Earth, the Moon, Mars, and so on. Following this are chapters on physical processes and on exploration. The final chapter of the book is Extra-Solar Planets: Searching for Other Planetary Systems.

Each chapter is a full-length narrative treatment of the subject at hand. Thus the Encyclopedias format allows readers to choose their own method for referring to the work. Those who wish specific information on limited topics can consult the A-Z Subject Index and then proceed to the desired topic from there. On the other hand, those who wish to obtain a full overview of a large subject can read the entire chapter on this subject from beginning to end; *e.g.,* The Sun. In fact, one can even read the entire Encyclopedia in sequence, in the manner of a textbook (or a novel), to obtain the ideal view of the complete subject of the solar system.

CHAPTER FORMAT

Each new chapter in the *Encyclopedia of the Solar System* begins at the top of a right-hand page, so that it may be quickly located. The authors name and affiliation are displayed at the beginning of the chapter. The chapter is organized according to a standard format, as follows:

- Title and Author
- Outline
- Glossary
- Defining Statement
- Body of the Chapter
- Cross-References
- Bibliography

OUTLINE

Each chapter in the Encyclopedia begins with an Outline that indicates the general content of the chapter. This outline serves two functions. First, it provides a brief preview of the text, so that the reader can get a sense of what is contained there without having to leaf through all the pages. Second, it serves to highlight important subtopics that will be discussed in the chapter. For example, the chapter Mars:Surface and Interior begins with the subtopic Mars Explorations.

The Outline is intended as an overview and thus it lists only the major headings of the chapter. In addition, extensive second-level and third-level headings will be found within the chapter.

GLOSSARY

The Glossary contains terms that are important to an understanding of the chapter and that may be unfamiliar to the reader. Each term is defined in the context of the particular chapter in which it is used. Thus the same term may appear as a Glossary entry in two or more chapters, with the details of the definition varying slightly from one chapter to another. The Encyclopedia includes approximately 500 glossary entries.

The following example is a glossary entry that appears with the chapter The Solar System and Its Place in the Galaxy.

> **Roche limit** The distance from a planet, within which another body will be disrupted because tidal forces from the planet exceed the self-gravity of the smaller body. For non-rotating bodies of equal density and zero strength, the Roche limit is about 2.2 planetary radii.

DEFINING STATEMENT

The text of each chapter in the Encyclopedia begins with a single introductory paragraph that defines the topic under discussion and summarizes the content of the chapter. For example, the chapter Planetary Radar begins with the following statement:

> Planetary radar astronomy is the study of solar system entities (the moon, asteroids, and comets, as well as the major planets and their ring systems) by transmitting a radio signal toward the target and then receiving and analyzing the echo. This field of research has primarily involved observations with Earth-based radar telescopes, but also includes certain experiments with the transmitter and/or the receiver on board a spacecraft orbiting or passing near a planetary object.

CROSS-REFERENCES

Chapters in the Encyclopedia have cross-references to other chapters. These cross-references appear within the text of the chapter, at the end of a paragraph containing material that is relevant to another chapter. The cross-references indicate related chapters that can be consulted for further information on the same topic, or for information on a related topic. For example, the chapter Titan has cross-references to Pluto and Charon, Triton, Planetary Impacts, and The Solar System at Radio Wavelengths.

BIBLIOGRAPHY

The Bibliography section appears as the last element in each chapter. This section lists recent secondary sources that will aid the reader in locating more information on the topic at hand. Review chapters and research papers that are important to a more detailed understanding of the topic are also listed here.

The Bibliography entries in this Encyclopedia are for the benefit of the reader, to provide references for further reading or research on the given topic. Thus they typically consist of a limited number of entries. They are not intended to represent a complete listing of all the materials consulted by the author or authors in preparing the chapter. The Bibliography is in effect an extension of the chapter itself, and it represents the authors choice as to the best sources available for additional information.

INDEX

The Subject Index for the *Encyclopedia of the Solar System* contains more than 4500 entries. Reference to the general coverage of a topic appears as a marginal entry, such as an entire section of an chapter devoted to the topic. References to more specific aspects of the topic then appear below this in an indented list.

ENCYCLOPEDIA WEBSITE

The *Encyclopedia of the Solar System* maintains its own editorial Web Page on the Internet at:
http://www.academicpress.com/solar/
This site gives information about the Encyclopedia project. It also features author-recommended links to other sites that provide information about the chapter topics of the Encyclopedia. The site will continue to evolve as more information becomes available.

THE SOLAR SYSTEM AND ITS PLACE IN THE GALAXY

Paul R. Weissman
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GLOSSARY

Asteroid: Rocky, carbonaceous, or metallic body, smaller than a planet and orbiting the Sun. Most asteroids are in semistable orbits between Mars and Jupiter, but others are thrown onto orbits crossing those of the major planets.

Astronomical unit: The distance from the Sun at which a massless particle in an unperturbed orbit would have an orbital period of 365.2568983 days, equal to $1.4959787066 \times 10^{11}$ m, or about 9.2953×10^{7} miles. Abbreviated AU, the astronomical unit is approximately the mean distance between the Earth and the Sun.

Comet: Body containing a significant fraction of ices, smaller than a planet and orbiting the Sun, usually in a highly eccentric orbit. Most comets are stored far from the planetary system in two large reservoirs: the Kuiper belt beyond the orbit of Neptune, and the Oort cloud at near-interstellar distances.

Eccentricity: Measure of the departure of an orbit from a perfect circle. A circular orbit has an eccentricity $e = 0$; an elliptical orbit has $0 < e < 1$; a parabolic orbit has $e = 1$; and a hyperbolic orbit has $e > 1$.

Ecliptic: Plane of the Earth's orbit around the Sun. The planets, most asteroids, and most of the short-period comets are in orbits with small or moderate inclinations relative to the ecliptic.

Heliocentric: Pertaining to a Sun-centered coordinate system.

Heliosphere: Cavity in the interstellar medium surrounding the solar system and dominated by the solar wind.

Inclination: Angle between the plane of the orbit of a planet, comet, or asteroid and the ecliptic plane, or between a satellite's orbit plane and the equatorial plane of its primary.

Jovian planet: Planet like Jupiter that is composed mostly of hydrogen, with helium and other gases, but possibly with a silicate/iron core; also called a gaseous planet. The Jovian planets are Jupiter, Saturn, Uranus, and Neptune.

Kuiper belt: Collection of some 10^{9} to 10^{10} or more icy bodies in low-eccentricity, low-inclination orbits beyond Neptune, extending out possibly to about 10^{3} AU.

Magnetosphere: Region of space around a planet or satellite that is dominated by its intrinsic magnetic field and associated charged particles.

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Main sequence: When stars are plotted on a graph of their luminosity versus their surface temperature (or color), most stars fall along a line extending from high-luminosity, high-surface-temperature stars to low-luminosity, low-surface-temperature stars. This plot is known as the Hertzsprung–Russell diagram and the line is known as the ''main sequence.'' Stars spend the majority of their lifetimes on the main sequence, during which they produce energy by hydrogen fusion occurring within their cores.

Meteoroid: Small fragment of an asteroid or comet that is in interplanetary space. When a meteoroid enters a planetary atmosphere and begins to glow from friction with the atmosphere, it is called a meteor. A fragment that survives atmospheric entry and can be recovered on the ground is called a meteorite.

Minor planet: Another term for an asteroid.

Oort cloud: Spherical cloud of some 10^{12} to 10^{13} comets surrounding the planetary system and extending out $\sim 10^5$ AU (0.5 parsec) from the Sun.

Orbit: Path of a planet, asteroid, or comet around the Sun, or of a satellite around its primary. Most bodies are in closed elliptical orbits. Some comets and asteroids are thrown into hyperbolic orbits, which are not closed, and so will escape the solar system.

Parallax: Apparent change in the position of a nearby star on the celestial sphere when measured from opposite sides of the Earth's orbit, usually given in seconds of arc.

Parsec: Distance at which a star would have a parallax of 1 second of arc, equal to 206,264.8 AU, or 3.261631 light-years; abbreviated as pc. One thousand parsecs are equal to a kiloparsec, which is abbreviated as kpc.

Perihelion: Point in the orbit of a planet, comet, or asteroid that is closest to the Sun.

Planet: Large body orbiting the Sun or another star, but not large enough to generate energy through nuclear fusion at its core. No formal definition of a planet exists and classifying exactly what is and is not a planet is often quite difficult. Some definitions demand that a planet should have an atmosphere, and/or a satellite, and/or be large enough to form itself into a sphere by self-gravity, and/or be able to gravitationally dominate its region of heliocentric space, but there are counter examples to every one of these requirements.

Planetesimal: Small body formed in the early solar system by accretion of dust and ice (if present) in the central plane of the solar nebula.

Protostar: Star in the process of formation, which is luminous owing to the release of gravitational potential energy from the infall of nebula material.

Roche limit: Distance from a planet within which another body will be disrupted because tidal forces from the planet exceed the self-gravity of the smaller body. For nonrotating bodies of equal density and zero strength, the Roche limit is about 2.2 planetary radii.

Satellite: Body in orbit around a planet. A satellite was recently discovered orbiting an asteroid, and several other asteroid satellites are suspected to exist.

Secular perturbations: Long-term changes in the orbit of a body caused by the distant gravitational attraction of the planets and other bodies.

Semimajor axis: Half of the major axis of an elliptical orbit. Commonly taken to be the mean distance of the orbit of an object from its primary, though not precisely correct.

Solar nebula: Cloud of dust and gas out of which the Sun and planetary system formed.

Solar wind: Supersonic expansion of the Sun's outer atmosphere through interplanetary space.

Terrestrial planet: Planet like the Earth with an iron core and a silicate mantle and crust. The terrestrial planets are Mercury, Venus, Earth, and Mars.

Zodiacal cloud: Cloud of interplanetary dust in the solar system, lying close to the ecliptic plane. The dust in the zodiacal cloud comes from both comets and asteroids.

I. INTRODUCTION

The origins of modern astronomy lie with the study of our solar system. When ancient humans first gazed at the skies, they recognized the same patterns of fixed stars rotating over their heads each night. They identified these fixed patterns, now called constellations, with familiar objects or animals, or stories from their mythologies and their cultures. But along with the fixed stars there were a few bright points of light that moved each night, slowly following similar paths through a belt of constellations around the sky. (The Sun and Moon also appeared to move through the same belt of constellations.) These wandering objects were the planets of our solar system. Indeed, the name "planet" derives from the Latin *planeta*, meaning "wanderer."

The ancients recognized five planets that they could see with their naked eyes. We now know that the solar system consists of nine planets (including the Earth), plus a myriad of smaller objects: satellites, rings, asteroids, comets, and dust. Discoveries of new objects, and new classes of objects, are continuing even today. Thus, our view of the solar system is constantly changing and evolving as new data and new theories to explain (or anticipate) the data become available.

The solar system we see today is the result of the complex interaction of physical, chemical, and dynamical processes that have shaped the planets and other bodies. By studying each of the planets and other bodies individually as well as collectively, we seek to gain an understanding of those processes and the steps that led to the current solar system. Many of those processes operated most intensely early in the solar system's history, as the Sun and planets formed from an interstellar cloud of dust and gas, 4.6 billion years ago. The first billion years of the solar system's history was a violent period as the planets cleared their orbital zones of much of the leftover debris from the process of planet formation, flinging small bodies into planet-crossing (and often planet-impacting) orbits or out to interstellar space. In comparison, the present-day solar system is a much quieter place, though all or most of these processes continue on a lesser scale today.

Our knowledge of the solar system has exploded in the past four decades as interplanetary exploration spacecraft have provided close-up views of all the planets except Pluto, as well as of a diverse collection of satellites, rings, asteroids, and comets. Earth-orbiting telescopes have provided an unprecedented view of the solar system, often at wavelengths not accessible from the Earth's surface. Ground-based observations have also continued to produce exciting new discoveries through the application of a variety of new technologies such as CCD (charge-coupled device) cameras, infrared detector arrays, adaptive optics, and powerful planetary radars. Theoretical studies have contributed significantly to our understanding of the solar system, largely through the use of advanced computer codes and high-speed, dedicated computers. Serendipity has also played an important role in many new discoveries.

Along with this increased knowledge have come numerous additional questions as we attempt to explain the complexity and diversity that we observe on each newly encountered world. The increased spatial and spectral resolution of the observations, along with *in situ* measurements of atmospheres, surface materials, and magnetospheres, has revealed that each body is unique, the result of the different combination of physical, chemical, and dynamical processes that formed and shaped it, as well as its different initial composition. Yet, even though each planet, satellite, and smaller object is now recognized to be very different from its neighbors, at the same time there are broad systematic trends and similarities that are clues to the collective history that the solar system has undergone.

We are also on the brink of an exciting new age of discovery with the detection of the first planet-sized bodies around nearby stars. Although the precise nature and origin of these extrasolar planets are still largely open questions, they are likely the prelude to the discovery of other planetary systems that may resemble our own.

A second astounding new discovery is the detection of possibly biogenic material in Martian meteorites (pieces of Mars rocks that were blasted off that planet by asteroid and/or comet impacts, and that have survived entry through the Earth's atmosphere). Although still very controversial, the detection of evidence of life evolving on a planet other than the Earth would suggest that life may also occur on other planets with the right physio-chemical resources and environment.

The goal of this chapter is to provide the reader with an introduction to the solar system. It seeks to provide a broad overview of the solar system and its constituent parts, to note the location of the solar system in the galaxy, and to describe the local galactic environment. Detailed discussion of each of the bodies that make up the solar system, as well as the processes that have shaped those bodies and the techniques for observing the planetary system, are provided in the following chapters of this Encyclopedia. The reader is referred to those chapters for more detailed discussions of each of the topics introduced here.

Some brief notes about planetary nomenclature will likely be useful. The names of the planets are all taken from Greek and Roman mythology (with the exception of Earth), as are the names of their satellites, with the exception of the Moon and the Uranian satellites, the latter being named after Shakespearean characters. The Earth is occasionally referred to as Terra, and the Moon as Luna, each the Latin version of their names. The naming system for planetary rings is different at each planet and includes descriptive names of the structures (at Jupiter), letters of the Roman alphabet (at Saturn), Greek letters and Arabic numerals (at Uranus), and the names of scientists associated with the discovery of Neptune (at Neptune).

Asteroids were initially named after Greek and Roman goddesses. As their numbers have increased, asteroids have been named after the family members of the discoverers, after observatories, universities, cities, provinces, historical figures, scientists, writers, artists, literary figures, and, in at least one case, the astronomer's cat. Initial discoveries of asteroids are designated by the year of their discovery and a letter code. Once the orbits of the asteroids are firmly established, they are given official numbers in the asteroid catalog; reliable orbits have been determined for about 8000 asteroids. The discoverer(s) of an asteroid are given the privilege of suggesting its name, if done so within 10 years from when it was officially numbered.

Comets are generally named for their discoverers, though in a few well-known cases, such as comets Halley and Encke, they are named for the individuals who first computed their orbits and linked several apparitions. Since some astronomers have discovered more than one short-period comet, a number is added at the end of the name to differentiate them, though this system is not applied to long-period comets. Comets are also designated by the year of their discovery and a letter code (a recently abandoned system used lowercase Roman letters and Roman numerals in place of the letter codes). The naming of newly discovered comets, asteroids, and satellites, as well as surface features on solar system bodies, is overseen by several commissions of the International Astronomical Union.

II. THE ARCHITECTURE OF THE SOLAR SYSTEM

The solar system consists of the Sun at its center, nine major planets, 63 known natural satellites (or moons), four ring systems, millions of asteroids (greater than 1 km in diameter), trillions of comets (greater than 1 km in diameter), the solar wind, and a large cloud of interplanetary dust. The arrangement and nature of all of these bodies are the result of physical and dynamical processes during their origin and subsequent evolution, and their complex interactions with one another. In studying the solar system, one of our primary goals is to understand those processes and to use that understanding to reconstruct the steps that led to the formation of the planetary system and its numerous components.

At the center of the solar system is the Sun, a rather ordinary main sequence star. The Sun is classified spectrally as a G2 dwarf, which means that it emits the bulk of its radiation in the visible region of the spectrum, peaking at yellow-green wavelengths. The Sun contains 99.85% of the mass in the solar system, but only about 0.5% of the angular momentum. The low angular momentum of the Sun results from the transfer of momentum to the accretion disk surrounding the Sun during the formation of the planetary system, and to a slow spin-down due to angular momentum being carried away by the solar wind.

The Sun is composed of hydrogen (75%), helium (23%), and heavier elements (2%). It produces energy through nuclear fusion at its center, with hydrogen atoms combining to form helium and releasing energy that eventually makes its way to the surface as visible sunlight. The central temperature of the Sun where fusion takes place is 15 million kelvins, whereas the temperature at the visible surface, the photosphere, is ~5800 K. The Sun has an outer atmosphere called the corona, which is visible only during solar eclipses, or through the use of specially designed telescopes called coronagraphs.

A star like the Sun is believed to have a typical lifetime of 9 to 10 billion years on the main sequence. The present age of the Sun (and the entire solar system) is estimated to be 4.6 billion years, so it is about halfway through its normal lifetime. The age estimate comes from radioisotope dating of meteorites.

A. DYNAMICS

The planets all orbit the Sun in roughly the same plane, known as the ecliptic (the plane of the Earth's orbit), and in the same direction, counterclockwise as viewed from the north ecliptic pole. Because of gravitational torques from the other planets, the ecliptic is not inertially fixed in space, and so dynamicists often use the invariable plane, which is the plane defined by the summed angular momentum vectors of all the planets.

To first order, the motion of any body about the Sun is governed by Kepler's laws of planetary motion. The laws of planetary motion are: (1) each planet moves about the Sun in an orbit that is an ellipse, with the Sun at one focus of the ellipse; (2) the straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time; and (3) the squares of the sidereal periods of the planets are in direct propor-

TABLE I
Planetary Orbits[a]

Planet	Semimajor axis (AU)	Eccentricity	Inclination (°)	Period (years)
Mercury	0.38710	0.205631	7.0048	0.2408
Venus	0.72333	0.006773	3.3947	0.6152
Earth	1.00000	0.016710	0.0000	1.0000
Mars	1.52366	0.093412	1.8506	1.8807
Jupiter	5.20336	0.048393	1.3053	11.856
Saturn	9.53707	0.054151	2.4845	29.424
Uranus	19.1913	0.047168	0.7699	83.747
Neptune	30.0690	0.008586	1.7692	163.723
Pluto	39.4817	0.248808	17.1417	248.02

[a] J2000, Epoch: January 1, 2000

tion to the cubes of the semimajor axes of their orbits. The laws of planetary motion, first set down by J. Kepler in 1609 and 1619, are easily shown to be the result of the inverse-square law of gravity with the Sun as the central body, and the conservation of angular momentum and energy. Parameters for the orbits of the nine planets are listed in Table I.

Because the planets themselves have finite masses, they exert small gravitational tugs on one another, which cause their orbits to depart from perfect ellipses. The major effects of these long-term or "secular" perturbations are to cause the perihelion point of each orbit to precess (rotate counterclockwise) in space, and the line of nodes (the intersection between the planet's orbital plane and the ecliptic plane) of each orbit to regress (rotate clockwise). Additional effects include slow oscillations in the eccentricity and inclination of each orbit, and the inclination of the planet's rotation pole to the planet's orbit plane (called the obliquity). For the Earth, these orbital oscillations have periods of 19,000 to 100,000 years. They have been identified with long-term variations in the Earth's climate, known as Milankovitch cycles, though the linking physical mechanism is not well understood.

Relativistic effects also play a small but detectable role. They are most evident in the precession of the perihelion of the orbit of Mercury, the planet deepest in the Sun's gravitational potential well. General relativistic effects add 43 arc-seconds per century to the precession rate of Mercury's orbit, which is 574 arc-sec per century. Prior to Einstein's statement of general relativity in 1916, it was thought that the excess in the precession rate of Mercury was due to a planet orbiting interior to it. This hypothetical planet was given the name Vulcan and extensive searches were conducted for it, primarily during solar eclipses. No planet was detected.

A more successful search for a new planet occurred in 1846. Two celestial mechanicians, J. C. Adams and U. J. J. Leverrier, independently used the observed deviations of Uranus from its predicted orbit to successfully predict the existence and position of Neptune. Neptune was found by J. G. Galle on September 23, 1846, using Leverrier's prediction.

More complex dynamical interactions are also possible, in particular when the orbital period of one body is a small-integer ratio of another's orbital period. This is known as a "mean motion resonance" and can have dramatic effects. For example, Pluto is locked in a 2 : 3 mean motion resonance with Neptune, and although the orbits of the two planets cross in space, the resonance prevents them from ever coming within 14 AU of each other. Also, when two bodies have identical perihelion precession rates or nodal regression rates, they are said to be in a "secular resonance," and similarly interesting dynamical effects can result. In many cases, mean motion and secular resonances can lead to chaotic motion, driving a body into a planet-crossing orbit, which will then lead to it being dynamically scattered among the planets, and eventually either ejected from the solar system or impacted on the Sun or a planet.

Chaos has become a very exciting topic in solar system dynamics in the past twenty years, and has been able to explain many features of the planetary system that were not previously understood. It should be noted that the dynamical definition of chaos is not always the same as the general dictionary definition. In celestial mechanics the term chaos is applied to describe systems that are not perfectly predictable over time. That is, small variations in the initial conditions, or the inability to specify the initial conditions precisely, will lead to a growing error in predictions of the long-term behavior of the system. If the error grows exponentially, then the system is said to be chaotic. However, the chaotic zone, the allowed area in phase space over which an orbit may vary, may still be quite constrained. Thus, although studies have found that the orbits of the planets are chaotic, this does not mean that Jupiter may one day become Earth-crossing, or vice versa. It means that the precise position of the Earth or Jupiter in its orbit is not predictable over very long periods of time. Since this happens for all the planets, then the long-term secular perturbations of the planets on one another are also not perfectly predictable, and can vary.

On the other hand, chaos can result in some extreme changes in orbits, with sudden increases in eccentricity that can throw small bodies onto planet-crossing orbits. One well-recognized case of this occurs near mean motion resonances in the asteroid belt, which causes small asteroids to be thrown onto Earth-crossing orbits, allowing for the delivery of meteoroids to the Earth.

The natural satellites of the planets and their ring systems (where they exist) are governed by the same dynamical laws of motion. Most satellites and all ring systems are deep within their planets' gravitational potential wells and so they move, to first order, on Keplerian ellipses. The Sun, planets, and other satellites all act as perturbers on the satellite orbits. Additionally, the equatorial bulge of the planet, caused by the planet's rotation, also acts as a perturber on the satellite and ring particle orbits. Finally, the satellites raise tides on the planets (and vice versa) and these result in yet another dynamical evolution, causing the planets to transfer rotational angular momentum to the satellite orbits (in the case of direct, or prograde orbits; satellites in retrograde orbits lose angular momentum). As a result, satellites may slowly move away from their planets into larger orbits (or smaller ones in the case of retrograde motion).

The mutual gravitational interactions can be quite complex, particularly in multi-satellite systems. For example, the three innermost Galilean satellites (so named because they were discovered by Galileo in 1610)—Io, Europa, and Ganymede—are locked in a 4 : 2 : 1 mean motion resonance with one another. In other words, Ganymede's orbital period is twice that of Europa and four times that of Io. At the same time, the other Jovian satellites (primarily Callisto), the Sun, and Jupiter's oblateness perturb the orbits, forcing them to be slightly eccentric and inclined to one another, while the tidal interaction with Jupiter forces the orbits to evolve outward. These competing dynamical processes result in considerable energy deposition in the satellites, which manifests itself as volcanic activity on Io, as a possible subsurface ocean on Europa, and as past tectonic activity on Ganymede.

This last example illustrates a very important point in understanding the solar system. The bodies in the solar system do not exist as independent, isolated entities, with no physical interactions between them. Even these "action at a distance" gravitational interactions can lead to profound physical and chemical changes in the bodies involved. To understand the solar system as a whole, one must recognize and understand the processes that were involved in its formation and its subsequent evolution, and that continue to act even today.

An interesting feature of the planetary orbits is their regular spacing. This is described by Bode's Law, first discovered by J. B. Titius in 1766 and brought to prominence by J. E. Bode in 1772. The law states that the semimajor axes of the planets in astronomical units can be roughly approximated by taking the sequence 0, 3, 6, 12, 24, ..., adding 4, and dividing by 10. The values for Bode's Law and the actual semimajor axes of the planets are listed in Table II. It can be seen that the law works very well for the planets as far as Uranus, but then breaks down. It also predicts a planet between Mars and Jupiter, the current location of the asteroid belt. Yet Bode's Law predates the dis-

TABLE II
Bode's Law
$[a_1 = 4/10,\ a_n = (3 \times 2^{n-2} + 4)/10]$

Planet	Semimajor axis (AU)	n	Bode's law
Mercury	0.387	1	0.4
Venus	0.723	2	0.7
Earth	1.000	3	1.0
Mars	1.524	4	1.6
Ceres	2.767	5	2.8
Jupiter	5.203	6	5.2
Saturn	9.537	7	10.0
Uranus	19.19	8	19.6
Neptune	30.07	9	38.8
Pluto	39.48	10	77.2

covery of the first asteroid by 35 years, as well as the discovery of Uranus by 15 years.

The reason why Bode's Law works so well is not understood. It appears to reflect the increasing ranges of gravitational dominance of successive planets at increasing heliocentric distances. However, it has been argued that Bode's Law may just be a case of numerology and not reflect any real physical principle at all.

Computer-based dynamical simulations have shown that the spacing of the planets is such that a body placed on a circular orbit between any pair of neighboring planets will likely be dynamically unstable. It will not survive over the history of the solar system unless protected by some dynamical mechanism such as a mean motion resonance with one of the planets. Over the history of the solar system, the planets have generally cleared their zones of smaller bodies through gravitational scattering. The larger planets, in particular Jupiter and Saturn, are capable of throwing small bodies onto hyperbolic orbits, which are unbound, allowing the objects to escape to interstellar space.

Thus, the comets and asteroids we now see in planet-crossing orbits must have been introduced into the planetary system relatively recently from storage locations either outside the planetary system or from protected, dynamically stable reservoirs. Because of its position at one of the Bode's law locations, the asteroid belt is a relatively stable resevoir. However, the asteroid belt's proximity to Jupiter's substantial gravitational influence results in some highly complex dynamics. Mean motion and secular resonances, as well as mutual collisions, act to remove objects from the asteroid belt and throw them into planet-crossing orbits. The failure of a major planet to grow in the asteroid belt is generally attributed to the gravitational effects of Jupiter disrupting the slow growth by accretion of a planetary-sized body in the neighboring asteroid belt region.

It is generally believed that comets originated as icy planetesimals in the outer regions of the solar nebula, at the orbit of Jupiter and beyond. Those proto-comets with orbits between the giant planets were gravitationally ejected, mostly to interstellar space. However, a fraction of the proto-comets were flung into distant but still bound orbits—the Sun's gravitational sphere of influence extends about 2×10^5 AU, or about 1 parsec. These orbits were sufficiently distant from the Sun that they were perturbed by random passing stars and by the tidal perturbation from the galactic disk. The stellar and galactic perturbations raised the perihelia of the comet orbits out of the planetary region. Additionally, the stellar perturbations randomized the inclinations of the comet orbits, forming a spherical cloud of comets around the planetary system and extending halfway to the nearest stars. This region is now called the Oort cloud, after J. H. Oort, who first suggested its existence in 1950. The current population of the Oort cloud is estimated at between 10^{12} and 10^{13} comets, with a total mass of about 40 Earth masses of material. About 80% of the Oort cloud population is in a dense core within $\sim 10^4$ AU of the Sun. Long-period comets (those with orbital periods greater than 200 years) observed passing through the planetary region come from the Oort cloud. Some of the short-period comets (those with orbital periods less than 200 years), such as Comet Halley, are long-period comets that have evolved to short-period orbits owing to repeated planetary perturbations.

A second reservoir of comets is the Kuiper belt beyond the orbit of Neptune, named after G. P. Kuiper, who in 1951 was one of the first to suggest its existence. Because no large planet grew beyond Neptune, there was no body to scatter away the icy planetesimals formed in that region. (The failure of a large planet to grow beyond Neptune is generally attributed to the increasing timescale for planetary accretion with increasing heliocentric distance.) This belt of remnant planetesimals may extend out several hundred AU from the Sun, perhaps even 10^3 AU, analogous to the disks of dust that have been discovered around main sequence stars such as Vega and Beta Pictoris (Fig. 1).

The Kuiper belt may contain many tens of Earth masses of comets. A slow gravitational erosion of comets from the Kuiper belt between 30 and 50 AU, due to the perturbing effect of Neptune, causes these comets to "leak" into the planetary region. Eventually some fraction of the comets evolve because of gravitational scattering by the Jovian planets into the inner planets region, where they can be observed as short-period comets. Short-period comets from the Kuiper belt are often called "Jupiter-family" or "ecliptic" comets, because most are in orbits that can have close encounters with Jupiter, and also are in orbits with inclinations close to the ecliptic plane. Based on the observed number of ecliptic comets, the number of comets in the Kuiper belt between 30 and 50 AU has been estimated at about 7×10^9 objects, with a total mass of about 0.1 Earth masses. Current studies suggest that the Kuiper belt has been collisionally eroded out to a distance of ~ 100 AU from the Sun, but that considerably more mass may still exist in orbits beyond that distance.

Although gravity is the dominant force in determining the motion of bodies in the solar system, other forces do come into play in special cases. Dust grains

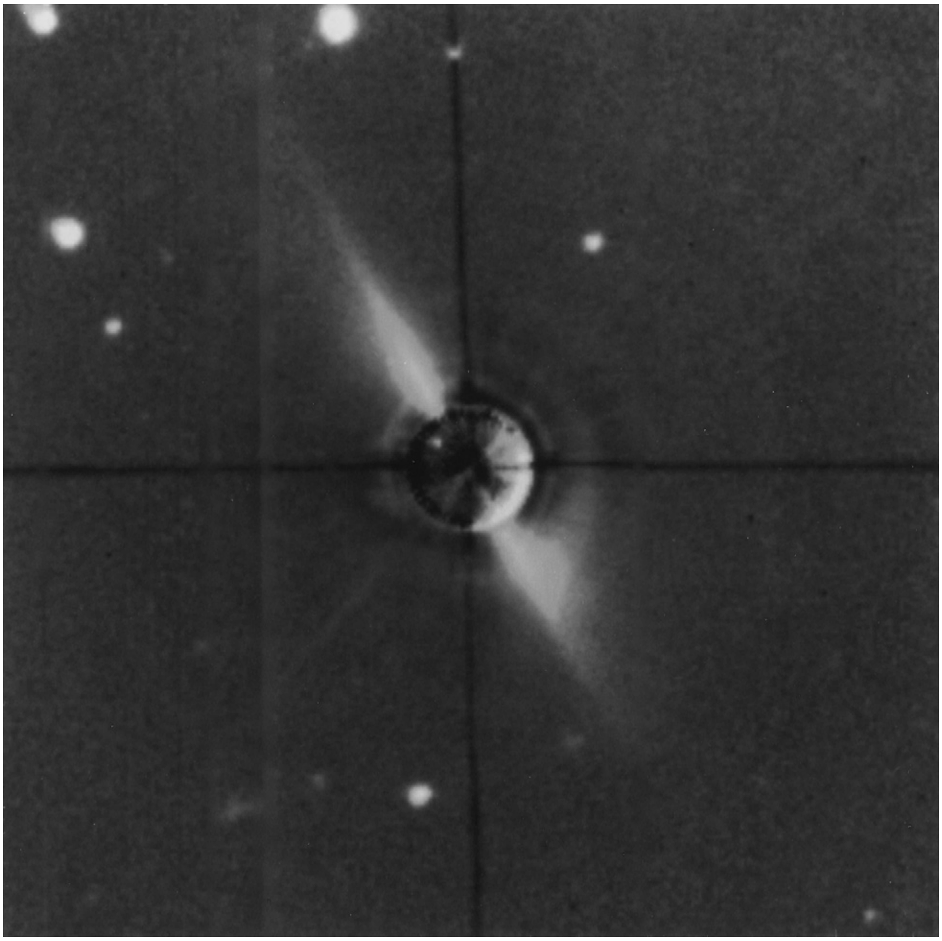


FIGURE 1 Coronagraphic image of the dust disk around the star Beta Pictoris, discovered by the *IRAS* satellite in 1983. The disk is viewed nearly edge on and extends ~900 AU on either side of the star. The occulting disk at the center blocks out the view of the central star and of the disk within ~150 AU of the star. Infrared data show that the disk does not extend all the way in to the star, but has an inner edge at about 30 AU from Beta Pictoris. The disk interior to that distance may have been swept up by the accretion of planets in the nebula around the star. This disk is a likely analog for the Kuiper belt around our own solar system.

produced by asteroid collisions or liberated from the sublimating icy surfaces of comets are small enough to also be affected by radiation pressure forces. For submicron grains, radiation pressure is sufficient to blow the grains out of the solar system. For larger grains, radiation pressure causes the grains to depart from Keplerian orbits. Radiation pressure can also cause larger grains to spiral slowly in toward the Sun through two different mechanisms, known as the Poynting–Robertson and Yarkovsky effects.

Electromagnetic forces play a role in planetary magnetospheres where ions are trapped and spiral back and forth along magnetic field lines, and in cometary Type I plasma tails where ions are accelerated away from the cometary coma, achieving fairly high energies. Dust grains trapped in planetary magnetospheres and in interplanetary space also respond to electromagnetic forces, though to a lesser extent than ions because of their much lower charge-to-mass ratios.

B. NATURE AND COMPOSITION

The solar nebula, the cloud of dust and gas out of which the planetary system formed, almost certainly exhibited a strong temperature gradient with heliocentric distance, hottest near the forming proto-Sun at its center and cooling as one moved outward through the planetary region. This temperature gradient is reflected in the compositional arrangement of the planets and their satellites versus heliocentric distance. Parts of the gradient are also preserved in the asteroid belt beween Mars and Jupiter and likely in the Kuiper belt beyond Neptune.

TABLE III
Physical Parameters for the Sun and Planets

Name	Mass (kg)	Equatorial radius (km)	Density (g cm^{-3})	Rotation period	Obliquity (°)	Escape velocity (km sec^{-1})
Sun	1.989×10^{30}	696,000	1.41	24.65–34 days	7.25[a]	617.7
Mercury	3.302×10^{23}	2,439	5.43	58.646 days	0	4.43
Venus	4.868×10^{24}	6,051	5.20	243.018 days	177.33	10.36
Earth	5.974×10^{24}	6,378	5.52	23.934 hr	23.45	11.19
Mars	6.418×10^{23}	3,396	3.93	24.623 hr	25.19	5.03
Jupiter	1.899×10^{27}	71,492	1.33	9.925 hr	3.08	59.54
Saturn	5.685×10^{26}	60,268	0.69	10.656 hr	26.73	35.49
Uranus	8.683×10^{25}	25,559	1.32	17.24 hr	97.92	21.33
Neptune	1.024×10^{26}	24,764	1.64	16.11 hr	28.80	23.61
Pluto	1.32×10^{22}	1,170	2.1	6.387 days	119.6	1.25

[a] Solar obliquity relative to the ecliptic.

The planets fall into two major compositional groups (Table III). The "terrestrial" or Earth-like planets are Mercury, Venus, Earth, and Mars, and are shown in Fig. 2. The terrestrial planets are characterized by predominantly silicate compositions with iron cores. This appears to result from the fact that they all formed close to the Sun, where it was too warm for ices to condense. Also, the modest masses of the terrestrial planets and their closeness to the Sun did not allow them to capture and retain hydrogen and helium directly from the solar nebula. The terrestrial planets all have solid surfaces that are modified to varying degrees by both cratering and internal processes (tectonics, weather, etc.). Mercury is the most heavily cratered because it has no appreciable atmosphere to protect it from impacts or weather to erode the cratered terrain, and also because encounter velocities with Mercury are very high that close to the Sun. Additionally, tectonic processes on Mercury appear to have been modest at best. Mars is next in degree of cratering, in large part because of its proximity to the asteroid belt. Also, Mars's thin atmosphere affords little protection against impactors. However, Mars also displays substantial volcanic and tectonic features, and evidence of erosion by wind and flowing water, the latter presumably having occurred early in the planet's history.

The surface of Venus is dominated by a wide variety of volcanic terrains. The degree of cratering on Venus is less than that on Mercury or Mars for two reasons: (1) Venus's thick atmosphere (surface pressure = 94 bars) breaks up smaller asteroids and comets before they can reach the surface and (2) vulcanism on the planet has covered over the older craters on the planet. The surface of Venus is estimated to be 600–800 million years in age. The Earth's surface is dominated by plate tectonics, in which large plates of the crust can move about the planet, and whose motions are reflected in features such as mountain ranges (where plates collide) and volcanic zones (where one plate dives under another). The Earth is the only planet with the right combination of atmospheric surface pressure and temperature to permit liquid water on its surface, and some 70% of the planet is covered by oceans. Craters on the Earth are rapidly erased by its active geology and weather, though the atmosphere provides protection only against very modest size impactors, on the order of 100 m diameter or less. Still, some 140 impact craters or their remnants have been found on the Earth's surface or under its oceans.

The terrestrial planets each have substantially different atmospheres. Mercury has a tenuous atmosphere arising from its interaction with the solar wind. Hydrogen and helium ions are captured directly from the solar wind, whereas oxygen, sodium, and potassium are likely the product of sputtering. In contrast, Venus has a dense CO_2 atmosphere with a surface pressure 94 times the pressure at the Earth's surface. Nitrogen is also present in the Venus atmosphere at a few percent relative to CO_2. The dense atmosphere results in a massive greenhouse on the planet, heating the surface to a mean temperature of 735 K. The middle and upper atmosphere contain thick clouds composed of H_2SO_4 and H_2O, which shroud the surface from view. However, it was recently discovered that thermal radia-

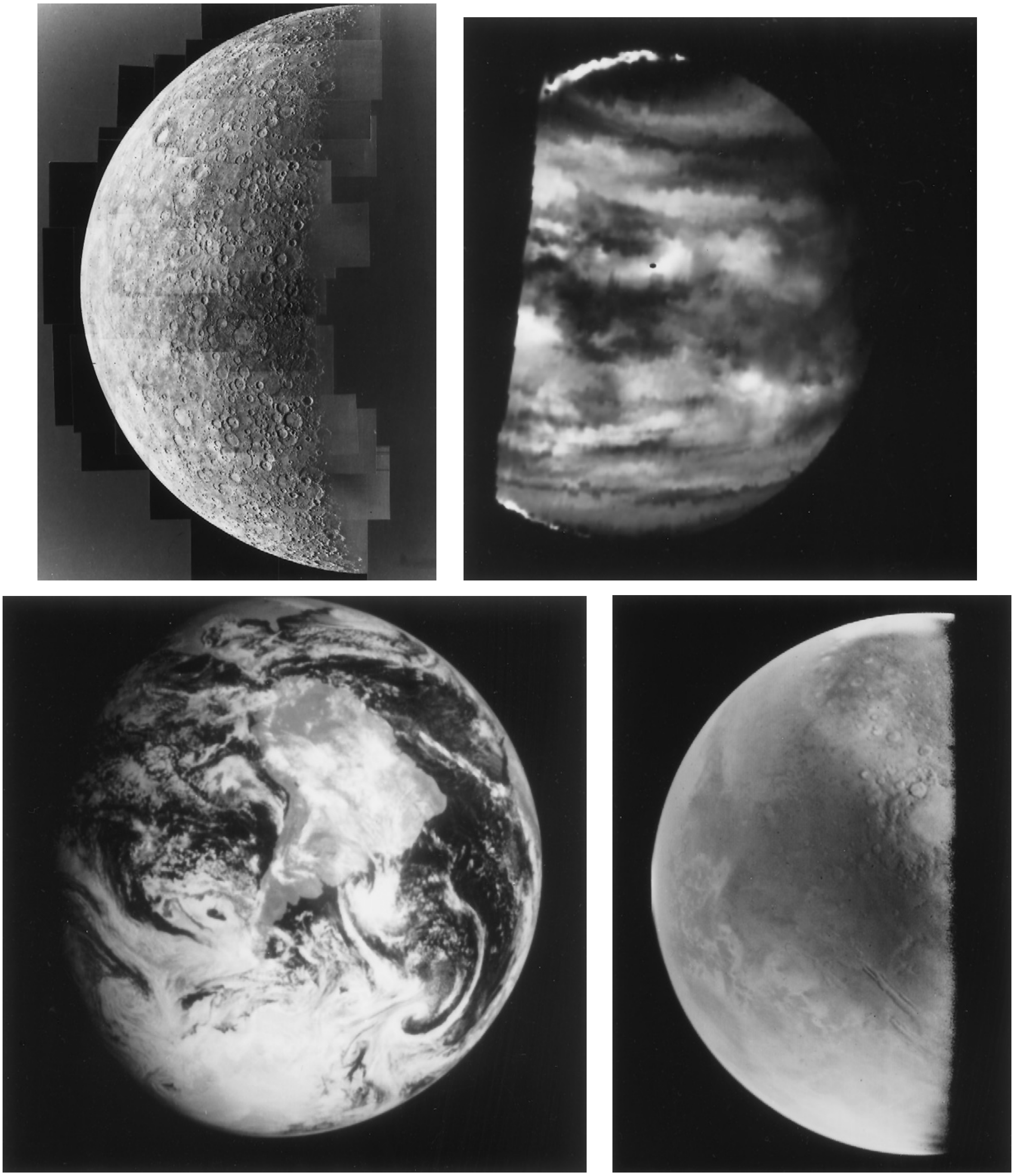


FIGURE 2 The terrestrial planets: the heavily cratered surface of Mercury as photographed by the *Mariner 10* spacecraft in 1974 (top left); clouds on the nightside of Venus, backlit by the intense infrared radiation from the planet's hot surface, as imaged by the *Galileo* NIMS instrument in 1990 (top right); South America and Antarctica as imaged by the *Galileo* spacecraft during a gravity assist flyby of the Earth in 1990 (bottom left); cratered and volcanic terrains on Mars, as photographed by the *Viking 1* spacecraft during its approach to the planet in 1976 (bottom right).

tion from the surface does penetrate the clouds, making it possible to view surface features through these infrared "windows."

The Earth's atmosphere is unique because of its large abundance of free oxygen, which is normally tied up in oxidized surface materials on other planets. The reason for this unusual state is the presence of life on the planet, which traps and buries CO_2 as carbonates and also converts the CO_2 to free oxygen. Still, the bulk of the Earth's atmosphere is nitrogen, 78%, with oxygen making up 21% and argon and water each about 1%. Various lines of evidence suggest that the composition of the Earth's atmosphere has evolved considerably over the history of the solar system, and that the original atmosphere was denser and had a much higher CO_2 content than the present-day atmosphere. Mars has a relatively modest CO_2 atmosphere with a mean surface pressure of only 6 millibars. The atmosphere also contains a few percent of N_2 and argon. Isotopic evidence and geologic features suggest that the past atmosphere of Mars may have been much denser and warmer, allowing liquid water to flow across the surface in massive floods.

The volatiles in the terrestrial planets' atmospheres (and the Earth's oceans) may have been contained in hydrated minerals in the planetesimals that originally formed the planets, and/or may have been added later from asteroid and comet bombardment as the planets dynamically cleared their individual zones of leftover planetesimals. It appears most likely that all of these reservoirs contributed some fraction of the volatiles on the planets.

The "Jovian" or Jupiter-like planets are Jupiter, Saturn, Uranus, and Neptune, and are shown in Fig. 3. The Jovian planets are also occasionally referred to as the "gas giants." They are characterized by low mean densities and thick hydrogen–helium atmospheres, presumably captured directly from the solar nebula during the formation of these planets. The composition of the Jovian planets is similar to that of the Sun, though more enriched in heavier elements. Because of this primarily gaseous composition and their high internal temperatures and pressures, the Jovian planets do not have solid surfaces. However, they may each have silicate–iron cores of several to tens of Earth masses of material at their centers.

The satellites of the Jovian planets are mostly icy bodies, predominantly water ice, with a few exceptions. One notable exception is Jupiter's innermost Galilean satellite, Io. However, Io has been heated tremendously over the history of the solar system by the tidal interaction noted in the previous section, and this can likely account for the loss of its volatile ices.

Because they formed at heliocentric distances where ices could condense, the giant planets may have initially had a much greater local density of solid material to grow from. This may, in fact, have allowed them to form ahead of the terrestrial planets interior to them. Studies of the dissipation of nebula dust disks around nearby solar-type protostars suggest that the timescale for the formation of giant planets is on the order of 10 million years or less. This is very rapid as compared with the ~100 million-year timescale currently estimated for the formation of the terrestrial planets (though questions have now been raised as to the correctness of that accretionary timescale). Additionally, the higher uncompressed densities of Uranus and Neptune (0.5 g cm^{-3}) versus Jupiter and Saturn (0.3 g cm^{-3}) suggest that the outer two giant planets contain a significantly lower fraction of gas captured from the nebula. This may mean that the outer pair formed later than the inner two giant planets, consistent with the increasing timescale for planetary accretion at larger heliocentric distances.

Because of their heliocentric arrangement, the terrestrial and Jovian planets are occasionally called the inner and outer planets, respectively, though sometimes the term inner planets is used to denote only Mercury and Venus, the planets interior to the Earth's orbit.

Pluto is an outlier to the system and is not easily classifiable as either a terrestrial or a Jovian planet. Rather, it bears the greatest resemblance to Triton, Neptune's large icy satellite that is slightly larger than Pluto, and to the icy planetesimals remaining in the Kuiper belt beyond the orbit of Neptune. (The retrograde orbit of Triton, the only one for a major satellite in the solar system, suggests that it may be an icy planetesimal that was captured from heliocentric space, and not formed coevally with Neptune in orbit around that planet.) Note also that Pluto does not readily fit into Bode's Law (see Table II). For these and other reasons, the designation of Pluto as a planet is often debated, and there are strong arguments both for and against the issue. As noted in the Glossary, the definition of a planet is an empirical one and often depends on the viewpoint of the observer. Because Pluto resides in the Kuiper belt, it is probably best thought of as the largest icy planetesimal to grow in that region of heliocentric space, rather than as a true planet. Pluto and its satellite Charon are shown in Fig. 4.

Pluto has a thin, extended atmosphere, probably methane and nitrogen, which is slowly escaping because of the low gravity of the planet. This puts it in a somewhat intermediate state between a freely outflowing cometary coma and a bound planetary atmo-

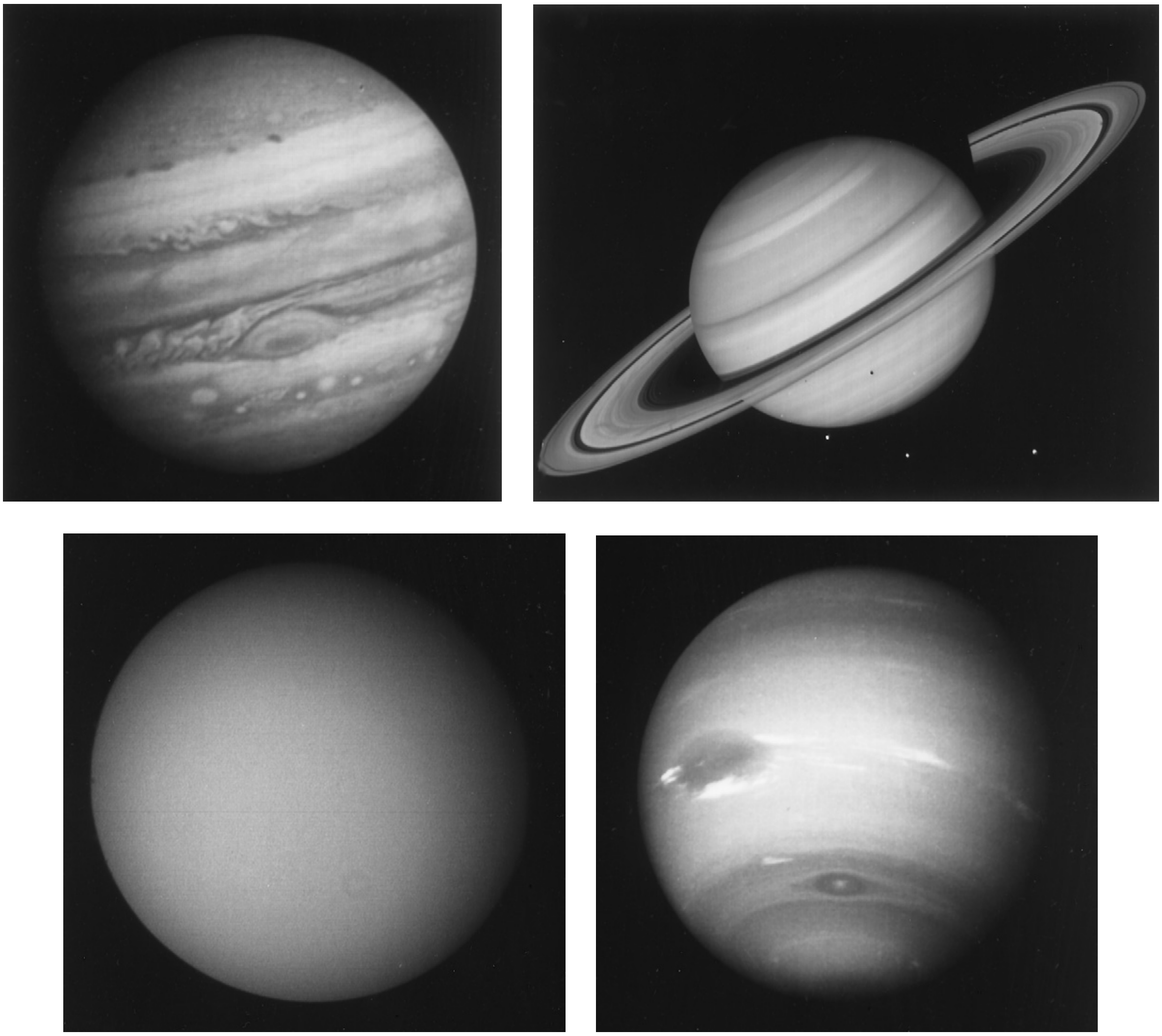


FIGURE 3 The Jovian planets: the complex, belted atmosphere of Jupiter with the Giant Red Spot at the lower center, as photographed by *Voyager 1* during its approach in 1979 (top left); Saturn, its beautiful ring system, and three of its satellites, as photographed by *Voyager 1* in 1980 (top right); the featureless atmosphere of Uranus, obscured by a high-altitude methane haze, as imaged by *Voyager 2* in 1986 (bottom left); Neptune's atmosphere displays several large storm systems and a banded structure, similar to Jupiter, as photographed by *Voyager 2* in 1989 (bottom right).

sphere. Spectroscopic evidence suggests that methane frost covers much of the surface of Pluto, whereas its satellite Charon appears to be covered with water frost. Nitrogen frost has also been detected on Pluto. The density of Pluto is ~ 2 g cm^{-3}, suggesting that the rocky component of the planet accounts for about 60–70% of its total mass.

There has been considerable speculation on the possibility of a major planet beyond Pluto, often dubbed "Planet X." The search program that discovered Pluto in 1930 was continued for many years afterward but failed to detect any other distant planet, even though the limiting magnitude was several times fainter than Pluto's visual magnitude of ~ 13.5. Other searches have been carried out, most notably by the *Infrared Astronomical Satellite* in 1983–1984. An automated algorithm was used to search for a distant planet in the *IRAS* data; it successfully "discovered" Neptune, but nothing else. Analyses of the orbits of Uranus and Neptune show no evidence of an additional perturber at greater heliocentric distances. Studies of the trajectories of the *Pioneer 10* and *11* and *Voyager 1* and *2* spacecraft have also yielded negative results. Analyses of the spacecraft trajectories allow one to set an upper

FIGURE 4 Pluto and its satellite Charon, as photographed by the *Hubble Space Telescope*. Pluto is the only planet that has not been imaged by a close spacecraft encounter.

limit on the unaccounted for mass within the orbit of Neptune of less than 3×10^{-6} solar masses ($M_\odot$), equal to about one Earth mass.

The compositional gradient in the solar system is perhaps best visible in the asteroid belt, whose members range from nickel–iron bodies in the inner belt, presumably the differentiated cores of larger asteroids that were subsequently disrupted by collisions, to volatile-rich carbonaceous bodies in the outer belt, which have never been melted or differentiated (Fig. 5). Thermally processed asteroids, including bodies like Vesta whose surface material resembles a basaltic lava flow, dominate the inner portion of the asteroid belt, at distances less than about 2.6 AU. At larger distances, out to the outer boundary of the main belt at about 3.3 AU, volatile-rich carbonaceous asteroids are dominant. The thermal gradient that processed the asteroids appears to be very steep and likely cannot be explained simply by the individual distances of these bodies from the forming proto-Sun. Rather, various special mechanisms such as magnetic induction, short-lived radioisotopes, or extreme solar flares have been invoked to try to explain the heating event that so strongly processed the inner half of the asteroid belt.

The largest asteroid is Ceres, at a mean distance of 2.77 AU from the Sun. (Note that Bode's law predicts a planet at 2.8 AU.) Ceres was the first asteroid discovered, by G. Piazzi on January 1, 1801. Ceres is 913 km in diameter, rotates in 9.08 hours, and appears to have a surface composition similar to that of carbonaceous chondrite meteorites. The second largest asteroid is Pallas, also a carbonaceous type with a diameter of 523 km. Pallas is also at 2.77 AU but its orbit has an unusually large inclination of 34.8°. Over 8000 asteroids have had their orbits accurately determined and have been given official numbers in the asteroid catalog; on the order of another 10^4 asteroids have been observed and have had preliminary orbits determined.

As a result of the large number of objects in the asteroid belt, impacts and collisions are frequent. Several "families" of asteroids have been identified by their closely grouped orbital elements and are likely fragments of larger asteroids that collided. Spectroscopic studies have shown that the members of these families often have very similar surface compositions, further evidence that they are related. The largest asteroids, such as Ceres and Pallas, are likely too large to be disrupted by impacts, but most of the smaller asteroids have probably been collisionally processed. Increasing evidence suggests that many asteroids may be "rubble piles," that is, asteroids that have been broken up but not dispersed by previous collisions, and that now form a single but poorly consolidated body.

Beyond the main asteroid belt there exist small groups of asteroids locked in dynamical resonances with Jupiter. These include the Hildas at the 3 : 2 mean motion resonance, the Thule group at the 4 : 3 resonance, and the Trojans, which are in a 1 : 1 mean motion resonance with Jupiter. The effect of the resonances is to prevent these asteroids from making close approaches to Jupiter, even though many of the asteroids are in Jupiter-crossing orbits.

The Trojans are particularly interesting. They are essentially in the same orbit as Jupiter but they librate about points 60° ahead and 60° behind the planet in its orbit, known as the Lagrange L_4 and L_5 points. These are pseudostable points in the three-body problem (Sun–Jupiter–asteroid) where bodies can remain dynamically stable for extended periods of time. Some estimates have placed the total number of objects in the Jupiter L_4 and L_5 Trojan swarms as equivalent to the population of the main asteroid belt. Trojan-type 1 : 1 librators have also been found for Mars and the Earth (one each) and have been searched for at the L_4 and L_5 points of the other giant planets, though none has been detected. It is interesting that the Saturnian satellite Tethys has two smaller satellites locked in Trojan-type librations in its orbit.

Much of what we know about the asteroid belt and the early history of the solar system comes from meteorites recovered on the Earth. It appears that the asteroid belt is the source of almost all recovered meteorites. A modest number of meteorites have been found that are from the Moon and from Mars, presumably blasted off of those bodies by asteroid and/or comet impacts. Cometary meteoroids are thought to be too fragile to survive atmospheric entry. In addition, cometary meteoroids typically encounter the Earth at higher velocities than asteroidal debris and thus are more likely to be fragmented and burned up during atmospheric entry. However, we may have cometary mete-

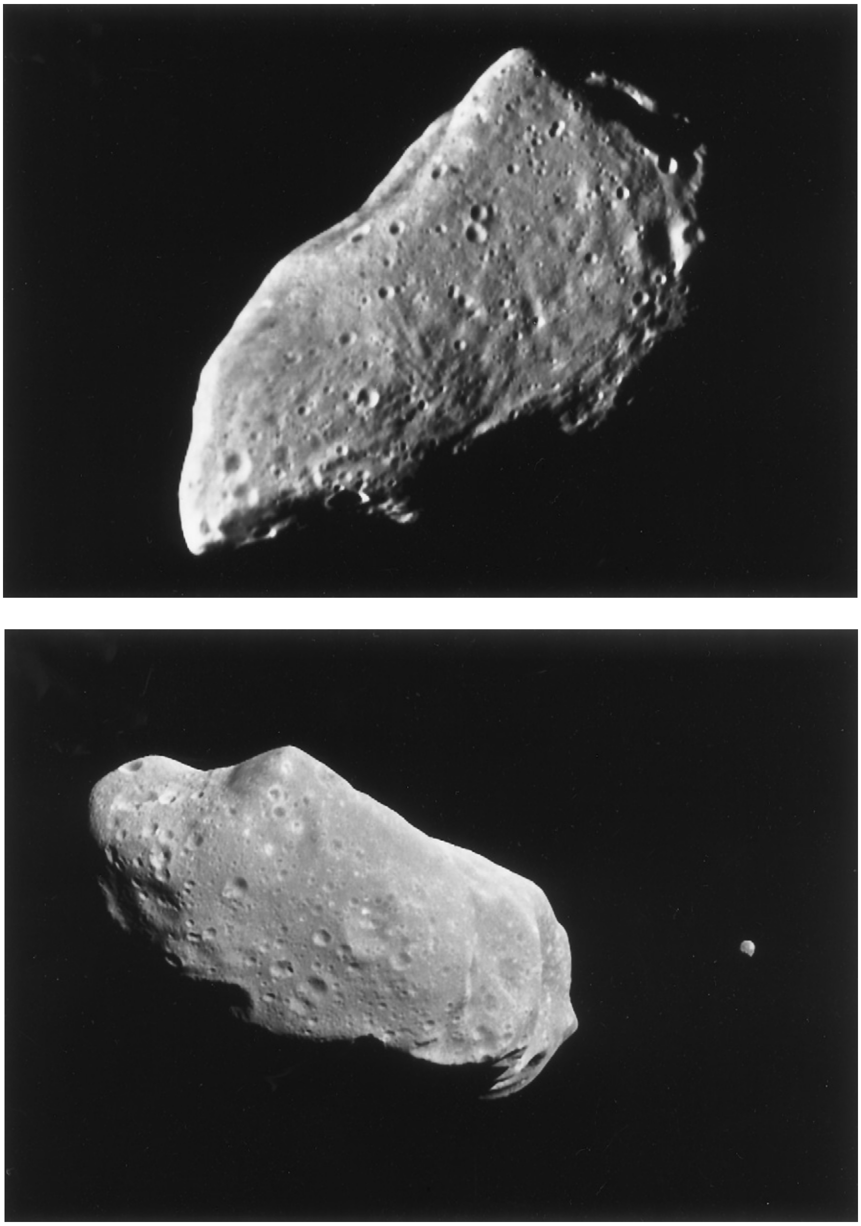


FIGURE 5 Three main belt asteroids: 951 Gaspra (top) and 243 Ida along with its small satellite Dactyl (bottom). All three asteroids are stony types and all exhibit heavily cratered surfaces. Gaspra is about 18 × 10 × 9 km in diameter, Ida is 54 × 24 × 15 km, and Dactyl is about 1.5 km in diameter. The asteroids were photographed by the *Galileo* spacecraft while it was en route to Jupiter, in 1991 and 1993, respectively. Ida's tiny satellite, Dactyl, was an unexpected discovery of two of *Galileo's* remote-sensing instruments, the Near Infrared Mapping Spectrometer and the Solid State Imaging system, during the flyby.

orites in our sample collections and simply not yet be knowledgeable enough to recognize them.

Recovered meteorites are roughly equally split between silicate and carbonaceous types, with a few percent being iron–nickel meteorites. The most primitive meteorites, that is, those that appear to show the least processing in the solar nebula, are the volatile-rich carbonaceous chondrites. However, even these meteorites show evidence of some thermal processing and of aqueous alteration, that is, processing in the presence of liquid water. Study of carbonaceous and ordinary (silicate) chondrites provides significant information on the composition of the original solar nebula, on the physical and chemical processes operating in the solar nebula, and on the chronology of the early solar system.

The other major group of primitive bodies in the solar system is the comets. Because comets formed farther from the Sun than the asteroids, in colder environments, they contain a significant fraction of volatile ices. Water ice is the dominant and most stable volatile. Typical comets also contain modest amounts of CO, CO_2, CH_4, NH_3, H_2CO, and CH_3OH, most likely in the form of ices, but possibly also contained within complex organic molecules. Organics make up a significant fraction of the cometary nucleus, as well as silicate grains. The American astronomer Fred Whipple described this icy-conglomerate mix as "dirty snowballs" (though the term "frozen mudball" may be more appropriate since the comets are more than 60% organics and silicates). It appears that the composition of comets is very similar to the condensed (solid) grains observed in dense interstellar cloud cores, with little or no evidence of processing in the solar nebula. Thus comets appear to be the most primitive bodies in the solar system. As a result, the study of comets is extremely valuable for those interested in learning about the origin of the planetary system and the conditions in the solar nebula 4.6 billion years ago.

Only one cometary nucleus, that of comet Halley, has been encountered by interplanetary spacecraft and imaged (Fig. 6). The nucleus was seen to be a highly irregular body, with dimensions of about $15 \times 8 \times 7$ km. It has been suggested that cometary nuclei are weakly bound conglomerations of smaller dirty snowballs, assembled at low velocity and low temperature in the outer regions of the solar nebula. Thus, comets may be "primordial rubble piles," in some ways similar to the asteroids, but with the difference that the "rubble" is primordially accreted macroscopic bodies in the solar nebula, rather than collisionally produced debris. A typical cometary nucleus is a few to ten kilometers in diameter.

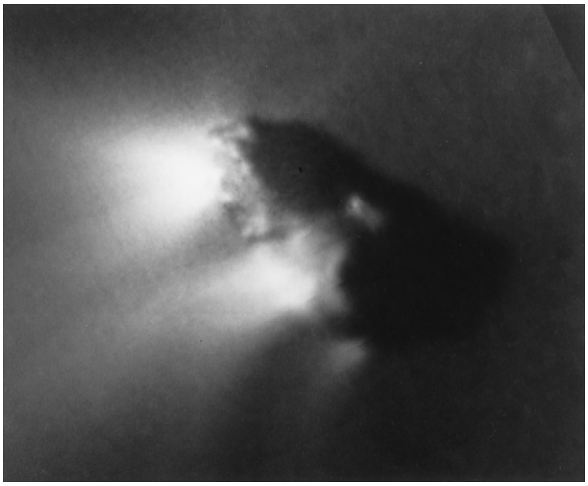


FIGURE 6 The nucleus of Halley's comet, as photographed by the *Giotto* spacecraft in 1986. The nucleus is irregularly shaped with dimensions of $15 \times 8 \times 7$ km. Jets of dust and gas are being emitted from active areas on the sunlit surface of the nucleus at left. (Copyright 1986 H. U. Keller, Max-Planck Institute for Aeronomie.)

Subtle and not-so-subtle differences in cometary compositions have been observed. However, it is not entirely clear if many of these differences are intrinsic or due to the physical evolution of cometary surfaces over many close approaches to the Sun. Because the comets that originated among the giant planets have all been ejected to the Oort cloud or to interstellar space, the compositional spectrum resulting from the heliocentric thermal profile is not spatially preserved as it has been in the asteroid belt. Although comets in the Kuiper belt are likely located close to their formation distances, physical studies of these distant objects are only just beginning. The data are not sufficient to reveal any compositional trends at the present time.

C. SATELLITES, RINGS, AND THINGS

The natural satellites of the planets, listed in Table IV, show as much diversity as the planets they orbit around. Among the terrestrial planets, the only known satellites are the Earth's Moon and the two small moons of Mars, Phobos and Deimos. The Earth's Moon is unusual in that it is so large relative to its primary (only Pluto's moon Charon is larger relative to its planet). The Moon has a silicate composition similar to the Earth's mantle and a very small iron core (Fig. 7).

It is now widely believed that the Moon formed as a result of a collision between the proto-Earth and another protoplanet about the size of Mars, late in the accretion of the terrestrial planets. Such "giant impacts" are now recognized as being capable of explaining many of the features of the solar system, such as the unusually high density of Mercury and the large obliquities of several of the planetary rotation axes. In the case of the Earth, the collision with another protoplanet resulted in the cores of the two planets merging, while a substantial fraction of the mantles of both bodies was thrown into orbit around the Earth where some of the material reaccreted to form the Moon. The tidal interaction between the Earth and Moon then slowly evolved the orbit of the Moon outward to its present position, at the same time slowing the rotation of both the Earth and the Moon. The giant impacts hypothesis is capable of explaining many of the features of the Earth–Moon system, including

TABLE IV
Orbital and Physical Parameters of Planetary Satellites

Name	Semimajor axis (10^3 km)	Orbital eccentricity	Orbital inclination (°)	Orbital period (days)	Mean radius (km)
Moon	384.40	0.0549	18–29	27.3216	1,737.4
Phobos	9.38	0.0151	1.08	0.319	13 × 11 × 9.2
Deimos	23.46	0.0003	1.79	1.262	7.5 × 6.1 × 5.2
J16 Metis	128.0	0.0	0.0	0.295	20
J15 Adrastea	129.0	0.0	0.0	0.298	10
J5 Amalthea	181.3	0.003	0.45	0.498	131 × 73 × 67
J14 Thebe	221.9	0.015	0.8	0.674	50
J1 Io	421.6	0.004	0.04	1.769	1,818
J2 Europa	670.9	0.010	0.47	3.552	1,560
J3 Ganymede	1,070	0.002	0.21	7.154	2,634
J4 Callisto	1,883	0.007	0.51	16.69	2,409
J13 Leda	11,094	0.148	26.70	238.7	5
J6 Himalia	11,480	0.163	27.63	250.6	85
J10 Lysithea	11,720	0.107	29.02	259.2	12
J7 Elara	11,737	0.207	24.77	259.6	40
J12 Ananke	21,200	0.169	147	631	10
J11 Carme	22,600	0.207	163	692	15
J8 Pasiphae	23,500	0.378	145	735	18
J9 Sinope	23,700	0.275	153	758	14
S18 Pan	133.6	0.0	0.0	0.575	10
S15 Atlas	137.6	0.0	0.0	0.602	19 × 17 × 14
S16 Prometheus	139.3	0.002	0.0	0.613	74 × 50 × 34
S17 Pandora	141.7	0.004	0.05	0.629	55 × 44 × 31
S11 Epimetheus	151.4	0.009	0.14	0.695	69 × 55 × 55
S10 Janus	151.5	0.007	0.34	0.695	97 × 95 × 77
S1 Mimas	185.5	0.020	1.53	0.942	199
S2 Enceladus	238.0	0.004	0.0	1.370	249
S3 Tethys	294.7	0.000	1.0	1.888	530
S14 Calypso	294.7	0.0	1.10	1.888	15 × 8 × 8
S13 Telesto	294.7	0.0	1.0	1.888	15 × 12 × 8
S4 Dione	377.4	0.002	0.02	2.737	560
S12 Helene	377.4	0.005	0.15	2.737	16
S5 Rhea	527.0	0.001	0.35	4.518	764
S6 Titan	1,222	0.029	0.33	15.945	2,575
S7 Hyperion	1,481	0.104	0.4	21.277	180 × 140 × 112
S8 Iapetus	3,561	0.028	14.72	79.330	718
S9 Phoebe	12,952	0.163	150	550.48	110

continues

the similarity in composition between the Moon and the Earth's mantle, the lack of a significant iron core within the Moon, and the high angular momentum of the Earth–Moon system.

Like most natural satellites, the Moon has tidally evolved to where its rotation period matches its revolution period in its orbit. This is known as "synchronous rotation." It results in the Moon showing the same face to the Earth at all times, though there are small departures from this because of the eccentricity of the Moon's orbit.

The Moon's surface displays a record of the intense bombardment that all the planets have undergone over the history of the solar system. Returned lunar samples have been age-dated based on decay of long-lived radioisotopes. This has allowed the determination of a chronology of lunar bombardment by comparing the sample ages with the crater counts on the lunar plains where the samples were collected. The lunar plains, or "maria," are the result of massive eruptions of lava during the first billion years or so of the Moon's history. The revealed chronology shows that the Moon *continued*

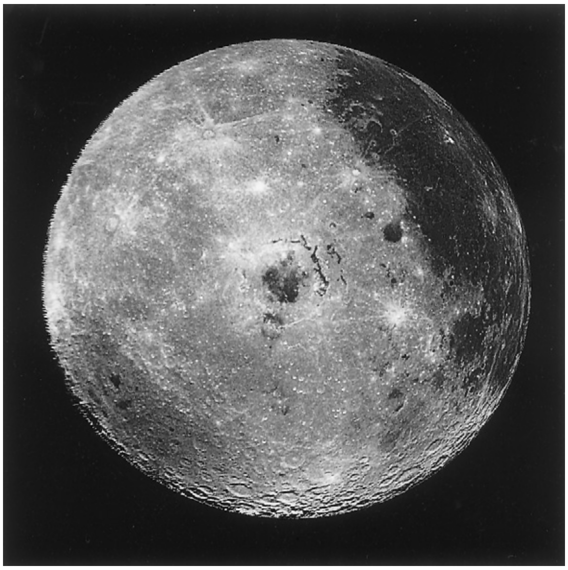
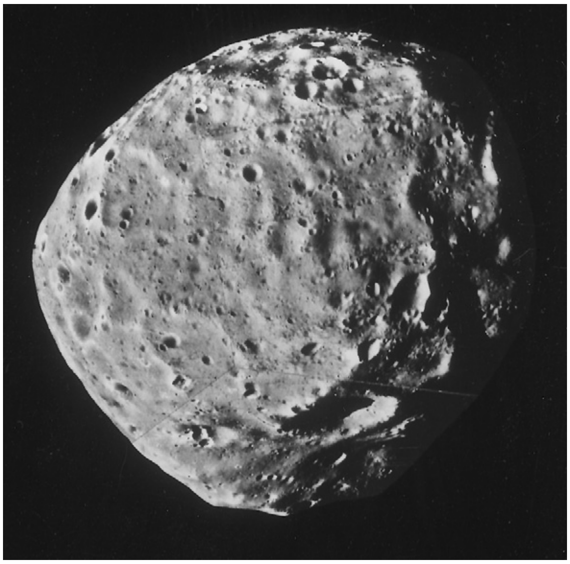
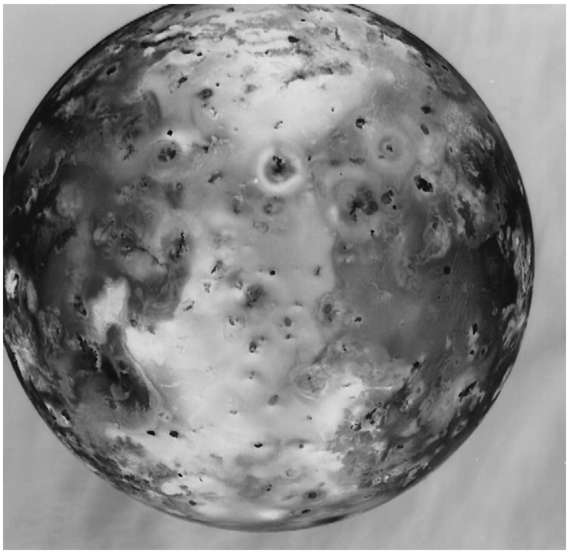
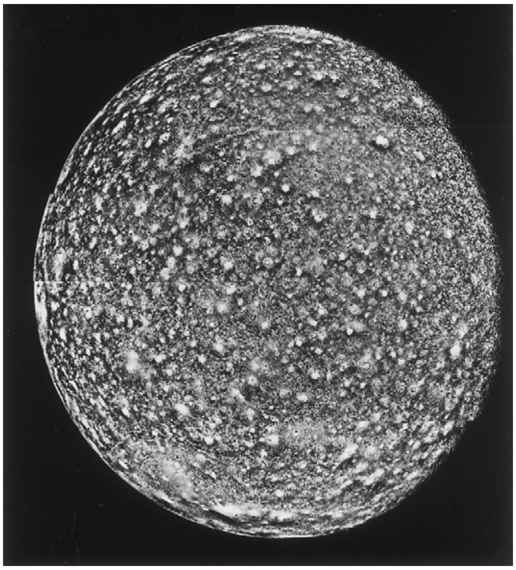
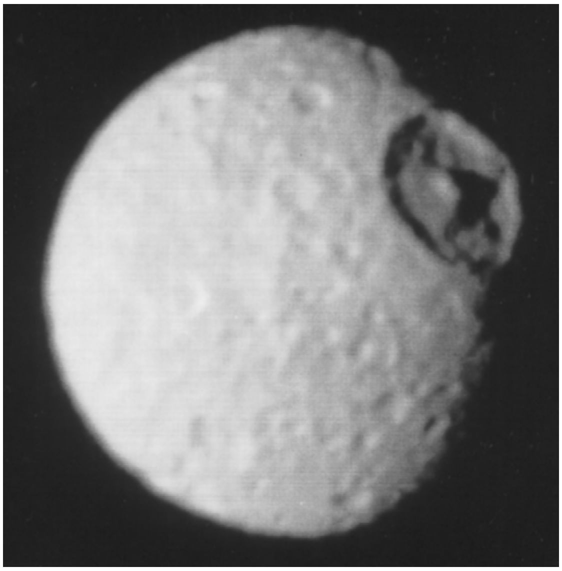
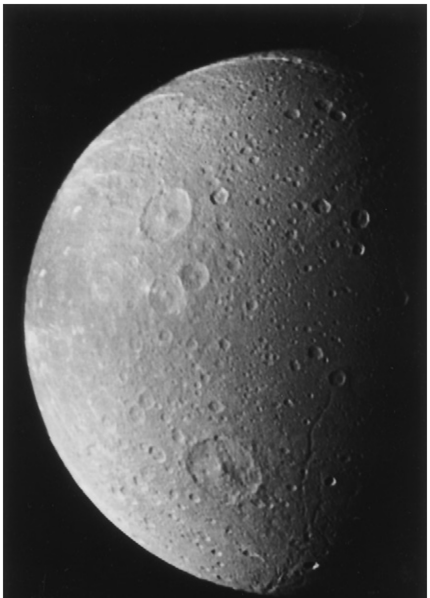
Name	Semimajor axis (10^3 km)	Orbital eccentricity	Orbital inclination (°)	Orbital period (days)	Mean radius (km)
U6 Cordelia	49.75	0.000	0.14	0.335	13
U7 Ophelia	53.76	0.010	0.09	0.376	15
U8 Bianca	59.16	0.001	0.16	0.435	21
U9 Cressida	61.78	0.000	0.04	0.464	31
U10 Desdemona	62.66	0.000	0.16	0.474	27
U11 Juliet	64.36	0.001	0.06	0.493	42
U12 Portia	66.10	0.000	0.09	0.513	54
U13 Rosalind	69.93	0.000	0.28	0.558	27
U14 Belinda	75.26	0.000	0.03	0.624	33
U15 Puck	86.00	0.000	0.31	0.762	77
U5 Miranda	129.8	0.003	3.40	1.413	236
U1 Ariel	191.2	0.003	0.0	2.520	579
U2 Umbriel	266.0	0.005	0.0	4.144	585
U3 Titania	435.8	0.002	0.0	8.706	789
U4 Oberon	582.6	0.001	0.0	13.46	761
S/1997 U1	7,169	0.082	140	580	30?
S/1997 U2	12,214	0.509	153	1290	60?
N3 Naiad	48.23	0.000	0.0	0.294	29
N4 Thalassa	50.08	0.000	4.5	0.311	40
N5 Despina	52.53	0.000	0.0	0.335	74
N6 Galatea	61.95	0.000	0.0	0.429	79
N7 Larissa	73.55	0.000	0.0	0.555	104 × 89
N8 Proteus	117.6	0.000	0.0	1.122	208
N1 Triton	354.8	0.000	157	5.877	1,353
N2 Nereid	5,513	0.751	29	360.14	170
P1 Charon	19.40	0.0076	96.16	6.387	593

experienced a massive bombardment between 4.0 and 3.5 billion years ago, known as the Late Heavy Bombardment. This time period is relatively late as compared with the 100–200 million years required to form the terrestrial planets and to clear their orbital zones of most interplanetary debris. Similarities in crater size distributions on the Moon, Mercury, and Mars suggest that the Late Heavy Bombardment swept over all of the terrestrial planets. Recent explanations for the Late Heavy Bombardment have focused on the possibility that it came from clearing of cometary debris from the outer planets zones. However, the detailed dynamical calculations of the timescales for that process are still in process.

Like almost all other satellites in the solar system, the Moon has no substantial atmosphere. There is a transient atmosphere due to helium atoms in the solar wind striking the lunar surface and being captured. Argon has been detected escaping from the surface rocks and being temporarily cold-trapped during the lunar night. Also, sodium and potassium have been detected, likely the result of sputtering of surface materials due to solar wind particles (as on Mercury).

Unlike the Earth's Moon, the two natural satellites of Mars are both small, irregular bodies and in orbits relatively close to the planet. In fact, Phobos, the larger and closer satellite, orbits Mars faster than the planet rotates. Both of the Martian satellites have surface compositions that appear to be similar to carbonaceous chondrites in composition. This has resulted in speculation that the satellites are captured asteroids. A problem with this hypothesis is that Mars is located close to the inner edge of the asteroid belt, where silicate asteroids dominate the population, and where carbonaceous asteroids are relatively rare. Also, both satellites are located very close to the planet and in near-circular orbits, which is unusual for captured objects.

In contrast to the satellites of the terrestrial planets, the satellites of the giant planets are numerous and are arranged in complex systems. Jupiter has four major satellites, easily visible in small telescopes from Earth, and 12 known, lesser satellites. The discovery of the four major satellites by Galileo in 1610 (as a result of which they are known as the Galilean satellites) was one of the early confirmations of the Copernican theory of a heliocentric solar system. The innermost Galilean

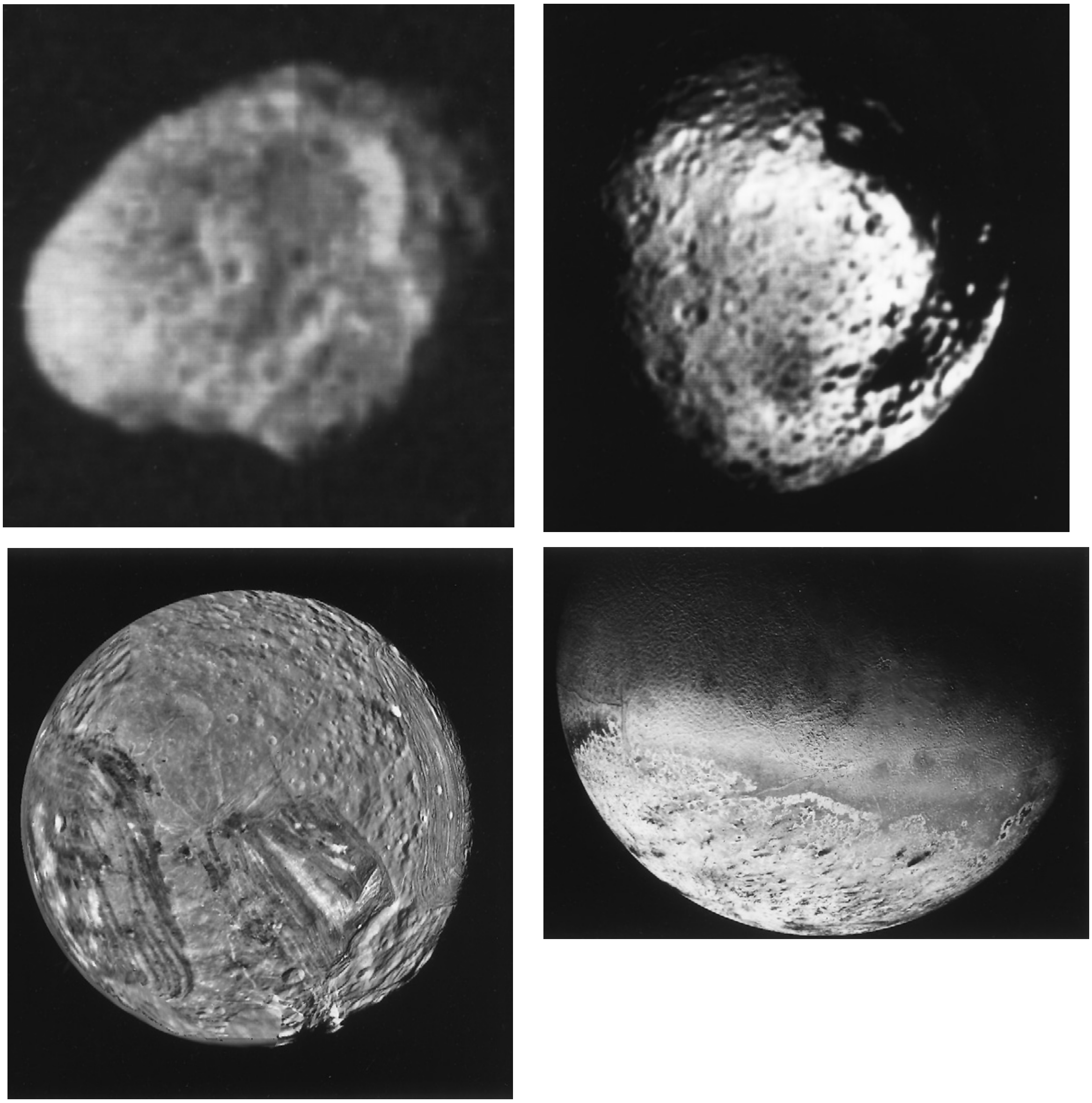


FIGURE 7 A sampling of satellites in the solar system: the heavily cratered surface of the Earth's Moon—at the center of the image is Mare Orientale, a large impact basin located on the east limb of the Moon as viewed from Earth (first page, top row, left); the larger of Mars's two moons, Phobos, is irregularly shaped and highly cratered (top row, right); the innermost Galilean satellite, Io, displays active vulcanism on its surface (first page, second row, left; the bright background is because the satellite was photographed against the disk of Jupiter); the outermost Galilean satellite, Callisto, displays a heavily cratered surface, likely dating back to the origin of the satellite system (first page, second row, right); one of Saturn's smaller satellites, Mimas, displays an immense impact crater on one hemisphere (first page, third row, left); the heavily cratered surface of Rhea, one of Saturn's intermediate-sized satellites, also showing some tectonic features (first page, third row, right); another Saturn satellite, Hyperion, is irregularly shaped and in chaotic rotation (second page, top row, left); Saturn's satellite Iapetus is black on one hemisphere and white on the other (second page, top row, right); Uranus's outermost major satellite, Miranda, has a complex surface morphology suggesting that the satellite was disrupted and reaccreted (second page, bottom row, left); Neptune's one large satellite, Triton, displays a mix of icy terrains (second page, bottom, right).

satellite, Io, is about the same size as the Earth's Moon and has active vulcanism on its surface as a result of Jupiter's tidal perturbation and the gravitational interaction with Europa and Ganymede (see previous section). The next satellite outward is Europa, a bit smaller than Io, which appears to have a thin ice crust overlying a possible liquid water ocean, also the result of tidal heating by Jupiter and the satellite–satellite interactions. Estimates of the age of the surface of Europa, based on counting impact craters, are very young, suggesting that the thin ice crust may repeatedly break up and re-form. The next satellite outward from Jupiter is Ganymede, the largest satellite in the solar system, even larger than the planet Mercury. Ganymede is another icy satellite and shows evidence of having been partially resurfaced at some time in its past. The final Galilean satellite is Callisto, another icy satellite that appears to preserve an impact record of comets and asteroids dating back to the origin of the solar system. As noted earlier, the orbits of the inner three Galilean satellites are locked into a 4 : 2 : 1 mean motion resonance.

The lesser satellites of Jupiter include several within the orbit of Io and a number at very large distances from the planet. The latter are likely captured comets and asteroids. The orbits of the eight outer satellites are divided into two closely spaced groups, and this suggests that they may be fragments of larger objects that were captured and then somehow disrupted. The most likely disruption process is collision with another object, and it is such a random collision itself, occurring within the gravitational sphere of Jupiter, that could have resulted in the dynamical capture.

All of the close-orbiting Jovian satellites (out to the orbit of Callisto) appear to be in synchronous rotation with Jupiter. However, rotation periods have been determined for two of the outer satellites, Himalia and Elara, and these appear to be around 10 to 12 hours, much shorter than their ~250-day periods of revolution about the planet.

Saturn's satellite system is very different from Jupiter's in that it contains only one large satellite, Titan, comparable in size to the Galilean satellites, a number of intermediate-sized satellites, and a host of smaller satellites. Titan is the only satellite in the solar system with a substantial atmosphere. Clouds of organic residue in its atmosphere prevent easy viewing of the surface of that moon. The atmosphere is primarily nitrogen and also contains methane and possibly argon. The surface temperature on Titan has been measured at 94 K and the surface pressure is 1.5 bar.

The intermediate and smaller satellites of Saturn all appear to have icy compositions and have undergone substantial processing, possibly as a result of tidal heating. Again, orbital resonances exist between a number of the satellites and most are in synchronous rotation with Saturn. An interesting exception is Hyperion, which is a highly nonspherical body and which appears to be in chaotic rotation. Another moon, Enceladus, has a ring of material in its orbit that likely has come from the satellite, as a result of either a recent massive impact or active vulcanism on the icy satellite. Another satellite, Tethys, has two companion satellites in the same orbit, which oscillate about the Trojan libration point for the Saturn–Tethys system ahead and behind Tethys, respectively. Yet another particularly interesting satellite of Saturn is Iapetus, which is dark on one hemisphere and bright on the other. The reason(s) for this unusual dichotomy in surface albedos are not known.

Saturn has one very distant satellite, Phoebe, which is in a retrograde orbit and which is suspected of being a captured comet, albeit a very large one. Phoebe is not in synchronous rotation, but rather has a period of about 10 hours.

The Uranian system consists of five intermediate-sized satellites and a number of smaller ones. Again, these are all icy bodies. These satellites also exhibit evidence of past heating and possible tectonic activity. The satellite Miranda is particularly unusual in that it exhibits a wide variety of complex terrains. It has been suggested that Miranda and possibly many other icy satellites were collisionally disrupted at some time in their history, and the debris then reaccreted in orbit to form the currently observed satellites. Such disruption/reaccretion phases may have even reoccurred on several occasions for a particular satellite over the history of the solar system.

Two small, distant satellites of Uranus, S/1997 U1 and S/1997 U2, were discovered in late 1997 in retrograde, eccentric orbits around the planet. These are likely captured objects.

Neptune's satellite system consists of one large icy satellite, Triton, and a number of smaller ones. Triton is slightly larger than Pluto and is unusual in that it is in a retrograde orbit. As a result, the tidal interaction with Neptune is causing the satellite's orbit to decay, and eventually Triton will collide with the planet. The retrograde orbit is often cited as evidence that Triton must have been captured from interplanetary space and did not actually form in orbit around the planet. Despite its tremendous distance from the Sun, Triton's icy surface displays a number of unusual terrain types that strongly suggest substantial thermal processing and possibly even current activity. The *Voyager 2* spacecraft photographed what appears to be plumes from "ice volcanos" on Triton.

The lesser satellites of Neptune are mostly in orbits close to the planet. However, Nereid is in a very distant orbit and is likely a captured object.

Pluto's satellite Charon is the largest satellite relative to its primary in the solar system, being slightly more than half the size of the planet. The Pluto–Charon system is fully tidally evolved. This means that the planet and the satellite both rotate with the same period, 6.39 days, which is also the revolution period of the satellite in its orbit. As a result, the planet and the satellite always show the same faces to each other. Although both Pluto and Charon are icy bodies, their densities appear to be somewhat different: $\sim$2 g cm^{-3} for Pluto versus $\sim$1.7 g cm^{-3} for Charon (though the uncertainty on Charon's density is rather high). This suggests that the satellite may have a smaller rocky component than the planet.

In addition to their satellite systems, all the Jovian planets have ring systems. As with the satellite systems, each ring system is distinctly different from that of its neighbors (Fig. 8). Jupiter has a single ring at 1.8 planetary radii, discovered by the *Voyager 1* spacecraft. Saturn has an immense, broad ring system extending between 1.0 and 2.3 planetary radii, easily seen in a small telescope from Earth. The ring system consists of three major rings, known as A, B, and C ordered from the outside in toward the planet, a diffuse ring labeled D inside the C ring and extending down to the top of the Saturnian atmosphere, and several other narrow, individual rings.

Closer examination by the Voyager spacecraft revealed that the A, B, and C rings were each composed of thousands of individual ringlets. This complex structure is the result of mean motion resonances with the Saturnian satellites, as well as with small satellites embedded within the rings themselves. Some of the small satellites act as gravitational "shepherds," focusing the ring particles into narrow ringlets. Ground-based observers recently discovered nine small satellites, 10–20 km in radius, embedded in the F ring, a thin, single ringlet outside the main ring system.

The Uranian ring system was discovered accidentally in 1977 during observation of a stellar occultation by Uranus. A symmetric pattern of five narrow dips in the stellar signal was seen on either side of the planet. Later observations of other stellar occultations found an additional five narrow rings. *Voyager 2* detected several more fainter, diffuse rings and provided detailed imaging of the entire ring system. The success with finding Uranus's rings led to similar searches for a ring system around Neptune using stellar occultations. Rings were detected but were not always symmetric about the planet, suggesting gaps in the rings. Subsequent *Voyager 2* imaging revealed large azimuthal concentrations of material in one of the six detected rings.

All the ring systems are within the Roche limits of their respective planets, at distances where tidal forces from the planet would disrupt any solid body, unless it was small enough and strong enough to be held together by its own material strength. This has led to the general belief that the rings are disrupted satellites, or possibly material that could never successfully form into satellites. Ring particles have typical sizes ranging from micron-sized dust to centimeter- to meter-sized objects, and appear to be made primarily of icy materials, though in some cases contaminated with carbonaceous materials.

Another component of the solar system is the zodiacal dust cloud, a huge, continuous cloud of fine dust extending throughout the planetary region and generally concentrated toward the ecliptic plane. The cloud consists of dust grains liberated from comets as the nucleus ices sublimate, and from collisions between asteroids. Comets are estimated to account for about two-thirds of the total material in the zodiacal cloud, with asteroid collisions providing the rest. Dynamical processes tend to spread the dust uniformly around the Sun, though some structure is visible as a result of the most recent asteroid collisions. These structures, or "bands" as they are known, are each associated with specific asteroid collisional families.

Dust particles will typically burn up due to friction with the atmosphere when they encounter the Earth, appearing as visible meteors. However, particles less than about 50 μm in radius have sufficiently large area-to-mass ratios that they can be decelerated high in the atmosphere at an altitude of about 100 km, and can radiate away the energy generated by friction without vaporizing the particles. These particles then descend slowly through the atmosphere and are eventually incorporated into terrestrial sediments. In the 1970s, NASA began experimenting with collecting interplanetary dust particles (IDPs; also known as "Brownlee particles" because of the pioneering work of D. Brownlee) using high-altitude U2 reconnaissance aircraft. Terrestrial sources of particulates in the stratosphere are rare and consist largely of volcanic aerosols and aluminum oxide particles from solid rocket fuel exhausts, each of which is readily distinguishable from extraterrestrial materials.

The composition of the IDPs reflects the range of source bodies that produce them, and include ordinary and carbonaceous chondritic material and suspected cometary particles. Since the degree of heating during atmospheric deceleration is a function of the encounter velocity, recovered IDPs are strongly biased toward

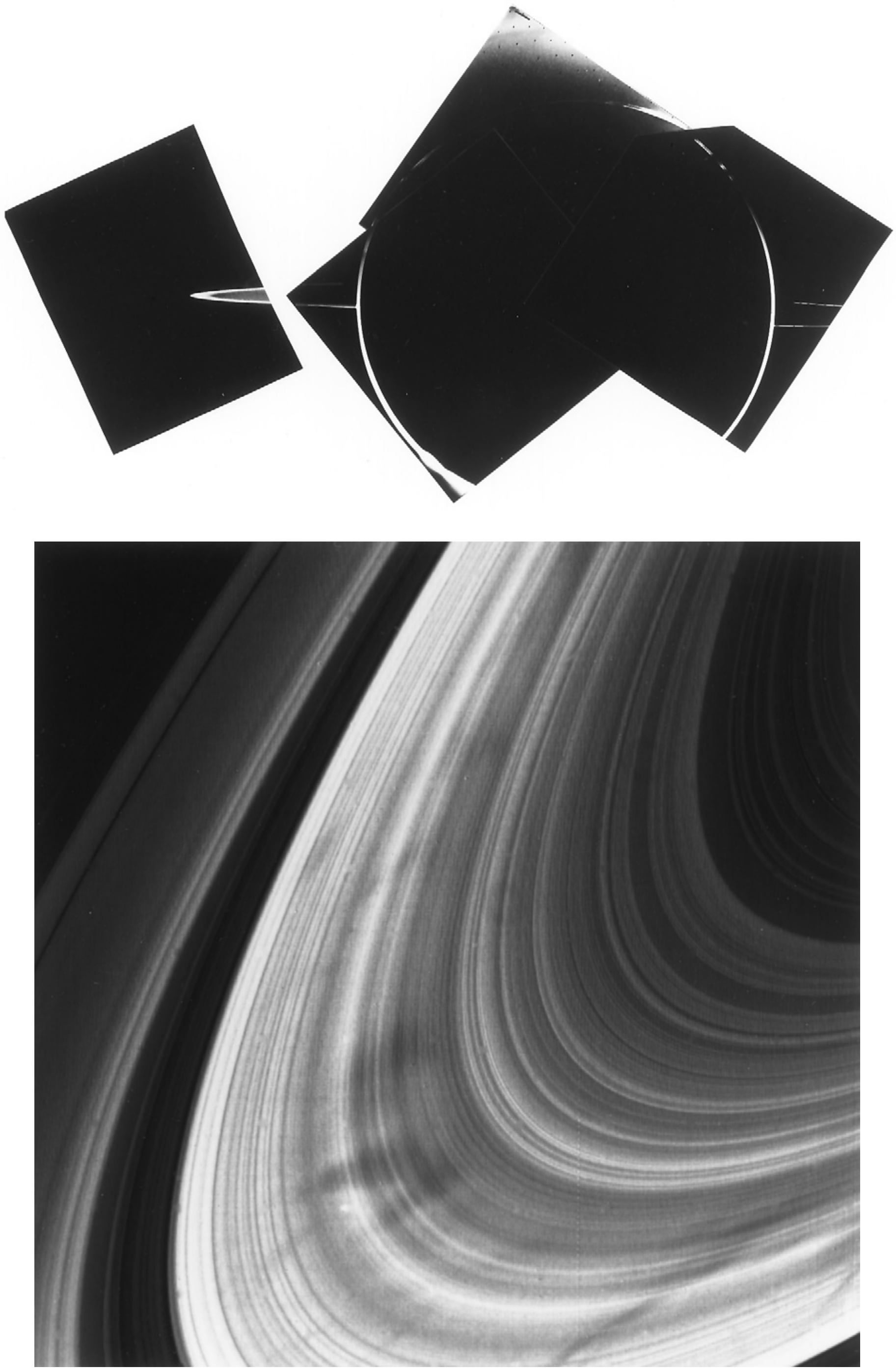
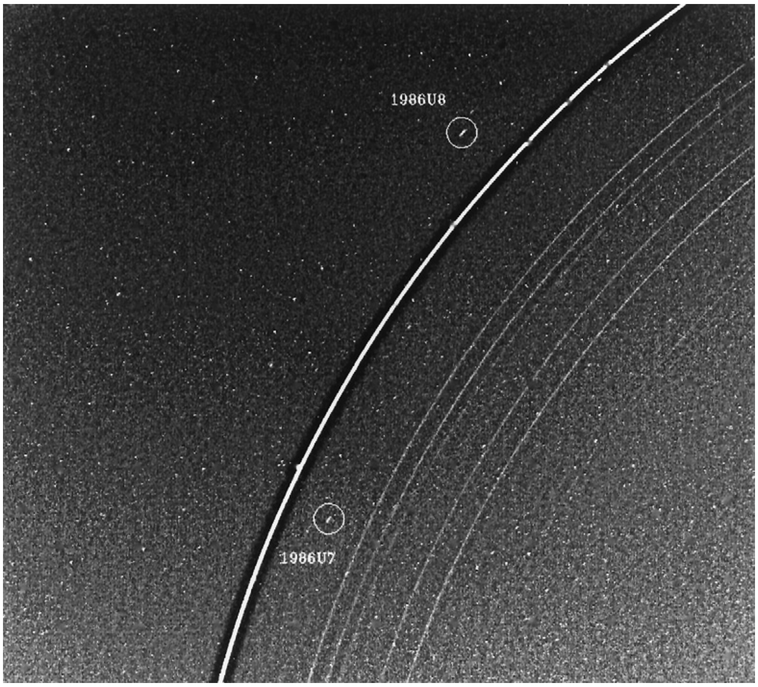


FIGURE 8 The ring systems of the Jovian planets: Jupiter's single ring photographed in forward-scattered light as the *Voyager 2* spacecraft passed behind the giant planet (top left); the multiple ringlets of Saturn's A and B rings (bottom left); the narrow rings of Uranus along with two "shepherd" satellites discovered by the *Voyager 2* spacecraft (top right); two of Neptune's rings showing the unusual azimuthal concentrations, as photographed by *Voyager 2* as it passed behind the planet; the greatly overexposed crescent of Neptune is visible at upper left in the image (bottom right).



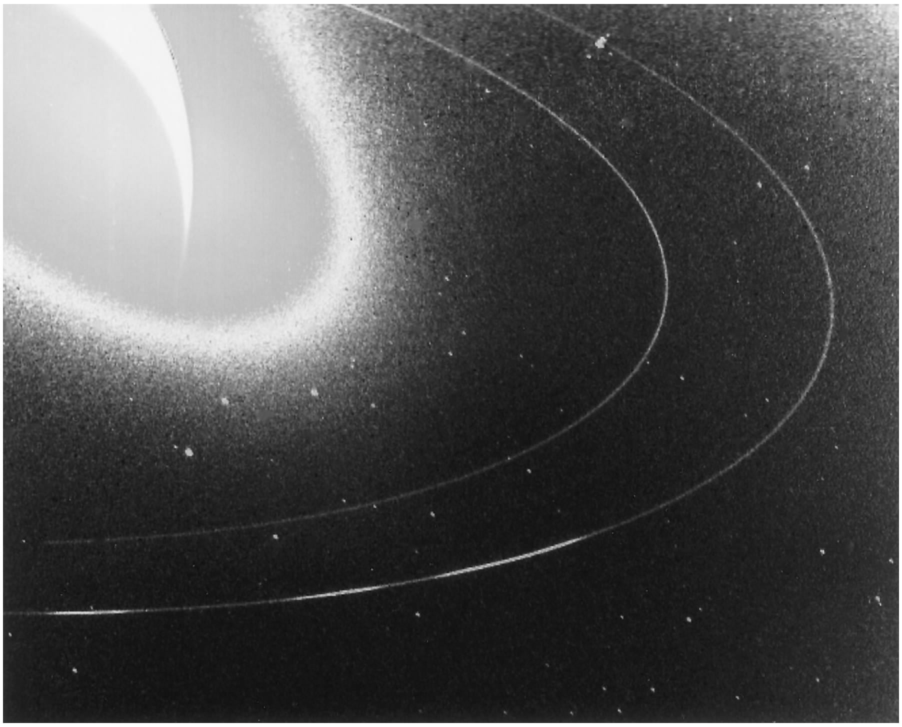


FIGURE 8 (*continued*)

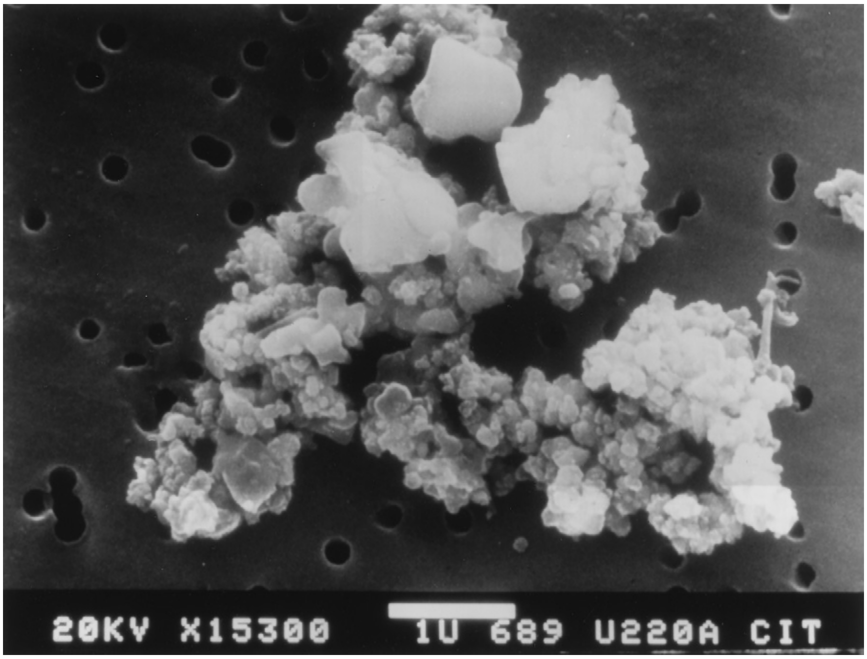


FIGURE 9 A scanning electron microscope image of a suspected cometary interplanetary dust particle (IDP). The IDP is a highly porous, apparently random collection of submicron silicate grains embedded in a carbonaceous matrix. The voids in the IDP may have once been filled with cometary ices. (Courtesy of D. Brownlee.)

asteroidal particles from the main belt, which approach the Earth in lower eccentricity orbits. Nevertheless, suspected cometary particles are included in the IDPs and represent our only laboratory samples of these icy bodies. The cometary IDPs show a random, "botroidal" (cluster-of-grapes) arrangement of submicron silicate grains (similar in size to interstellar dust grains), intimately mixed in a carbonaceous matrix. Voids in IDP particles may have once been filled by cometary ices. An example of a suspected cometary IDP is shown in Fig. 9.

Extraterrestrial particulates are also collected on the Earth in Antarctic ice cores, in meltponds in Greenland, and as millimeter-sized silicate and nickel–iron melt products in sediments. Recently, it has been shown that the IDP component in terrestrial sediments can be determined by measuring the abundance of ^{3}He. ^{3}He has normal abundances in terrestrial materials of 10^{-6} or less. The ^{3}He is implanted in the grains during their exposure to the solar wind. Using this technique, one can look for variations in the infall rate of extraterrestrial particulates over time, and such variations are seen, sometimes correlated with impact events on the Earth.

A largely unseen part of the solar system is the solar wind, an ionized gas that streams continuously into space from the Sun. The solar wind is composed primarily of protons (hydrogen nuclei) and electrons with some alpha particles (helium nuclei) and trace amounts of heavier ions. It is accelerated to supersonic speed in the solar corona and streams outward at a typical velocity of 400 km sec^{-1}. The solar wind is highly variable, changing with both the solar rotation period of 25 days and with the 22-year solar cycle, as well as on much more rapid timescales. As the solar wind expands outward, it carries the solar magnetic field with it in a spiral pattern caused by the rotation of the Sun. The solar wind was first inferred in the late 1940s based on observations of cometary plasma tails. The theory of the supersonic solar wind was first described by E. N. Parker in 1958, and the solar wind itself was detected in 1961 by the *Explorer 10* spacecraft in Earth orbit and in 1962 by the *Mariner 2* spacecraft while it was en route to a flyby of Venus.

The solar wind interaction with the planets and the other bodies in the solar system is also highly variable, depending primarily on whether or not the body has its own intrinsic magnetic field. For bodies without a magnetic field, such as Venus and the Moon, the solar wind impinges directly on the top of the atmosphere or on the solid surface, respectively. For bodies like the Earth or Jupiter, which do have magnetic fields, the field acts as a barrier and deflects the solar wind around it. Because the solar wind is expanding at super-

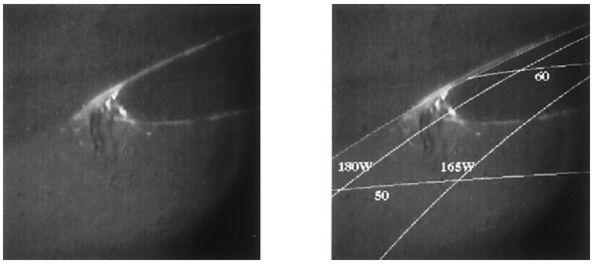


FIGURE 10 The auroral ring over the north polar region of Jupiter, as imaged by the *Galileo* spacecraft.

sonic speeds, a shock wave, or "bow shock," develops at the interface between the interplanetary solar wind and the planetary magnetosphere or ionosphere. The planetary magnetospheres can be quite large, extending out some 10 to 20 planetary radii upstream (sunward) of the Earth, and over 100 radii from Jupiter. Solar wind ions can leak into the planetary magnetospheres near the poles and these can result in visible aurora, which have been observed on both the Earth and Jupiter (Fig. 10). As it flows past the planet, the interaction of the solar wind with the planetary magnetospheres results in huge magneto-tail structures that often extend over interplanetary distances.

All the Jovian planets, as well as the Earth, have substantial magnetic fields and thus planetary magnetospheres. Mercury has a weak magnetic field but Venus has no detectable field. Mars has a patchy field, indicative of a past magnetic field at some point in the planet's history, but no organized magnetic field at this time. Nothing is known about Pluto's magnetic field. The *Galileo* spacecraft recently detected a magnetic field associated with Ganymede, the largest of the Galilean satellites. However, no magnetic field was detected for Europa or Callisto. The Earth's Moon has no magnetic field.

The most visible manifestation of the solar wind is cometary plasma tails, which result when the evolving gases in the cometary comae are ionized by sunlight and by charge exchange with the solar wind and then accelerated by the solar magnetic field. The ions stream away from the cometary comae at high velocity in an antisunward direction. Structures in the tail are visible as a result of fluorescence by CO^+ and other ions. Before the solar wind was suggested by Parker, its existence was inferred by L. Biermann based on his analysis of observations of cometary plasma (ion) tails.

At some distance from the Sun, far beyond the orbits of the planets, the solar wind reaches a point where the ram pressure from the wind is equal to the external pressure from the local interstellar medium flowing past the solar system. A shock will likely develop upstream (sunward) of that point and the solar wind will be decelerated from supersonic to subsonic. This shock is currently estimated to occur at about 90 ± 20 AU. Beyond this distance is a region still dominated by the subsonic solar plasma, extending out another 30–50 AU or more. The outer boundary of this region is known as the heliopause and defines the limit between solar system-dominated plasma and the interstellar medium. It is not currently known if the flow of interstellar medium past the solar system is supersonic or subsonic. If it is supersonic, then there must additionally be a "bow shock" beyond the heliopause, where the interstellar medium encounters the obstacle presented by the heliosphere. A diagram of the major features of the heliosphere is shown in Fig. 11.

The *Pioneer 10* and *11* and *Voyager 1* and *2* spacecraft, which are currently leaving the planetary region on hyperbolic trajectories, have been searching for the heliopause. These spacecraft are currently at distances ranging between 50 and 70 AU. There have been some indications from the Voyager plasma wave instruments that the spacecraft are approaching the heliopause but have not yet reached it. Based on the Voyager data, the heliopause is estimated to be at 110 to 160 AU from the Sun. The Voyager spacecraft are expected to continue to send measurements of this region of space until the year 2015, when they are each expected to be at about 130 AU from the Sun.

To many planetary scientists, the heliopause defines the boundary of the solar system, since it marks the changeover from a solar wind to an interstellar medium-dominated space. However, as already noted, the

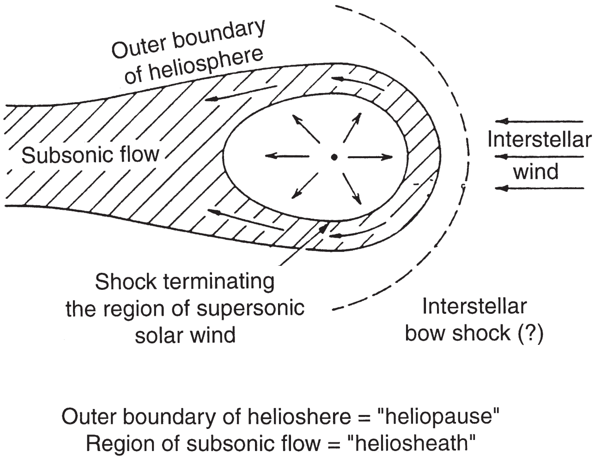


FIGURE 11 The major boundaries predicted for the heliosphere. (Reprinted with kind permission from Kluwer Academic Publishers, Axford, *Space Sci. Rev.* **78**, 9–14, Fig. 1, copyright © 1996.)

Sun's gravitational sphere of influence extends out much farther, to approximately 2×10^5 AU, and there are bodies in orbit around the Sun at those distances. These include the Kuiper belt, which may extend out to $\sim 10^3$ AU, and the Oort cloud, which is populated to the limits of the Sun's gravitational field.

III. THE ORIGIN OF THE SOLAR SYSTEM

Our knowledge of the origin of the Sun and the planetary system comes from two sources: study of the solar system itself, and study of star formation in nearby giant molecular clouds. The two sources are radically different. In the case of the solar system, we have an abundance of detailed information on the planets, their satellites, and numerous small bodies. But the solar system we see today is a highly evolved system that has undergone massive changes since it first condensed from the natal cloud, and we must learn to recognize which qualities reflect that often violent evolution and which truly record conditions at the time of solar system formation.

In contrast, when studying even the closest star-forming regions (which are about 140 pc from the Sun), we are handicapped by a lack of adequate resolution and detail. In addition, we are forced to take a "snapshot" view of many young stars at different stages in their formation, and from that attempt to generate a time-ordered sequence of the many different stages and processes involved. When we observe the formation of other stars we need also to recognize that some of the observed processes or events may not be applicable to the formation of our own Sun and planetary system.

Still, a coherent picture has emerged of the major events and processes in the formation of the solar system. That picture assumes that the Sun is a typical star and that it formed in a similar way to many of the low-mass protostars we see today.

The birthplace of stars is giant molecular clouds in the galaxy. These huge clouds of molecular hydrogen have masses of 10^5 to 10^6 solar masses, $M_\odot$. Within these clouds are denser regions or "cores" where star formation actually takes place. Some process, perhaps the shock wave from a nearby supernova, triggers the gravitational collapse of a cloud core. Material falls toward the center of the core under its own self-gravity and a massive object begins to grow at the center of the cloud. Heated by the gravitational potential energy of the infalling matter, the object becomes self-luminous, and is then described as a "protostar." Although central pressures and temperatures are not yet high enough to ignite nuclear fusion, the protostar begins to heat the growing nebula around it. The timescale of the infall of the cloud material for a solar-mass cloud is about 10^6 years.

The infalling cloud material consists of both gas and dust. The gas is mostly hydrogen (77%) with helium (21%) and other gases. The dust is a mix of interstellar grains, including silicates, organics, and condensed ices. A popular model suggests that the silicate grains are coated with icy-organic mantles. As the dust grains fall inward, they experience a pressure from the increasing density of gas toward the center of the nebula. This slows and even halts the inward radial component of their motion. However, the dust grains can still move vertically with respect to the central plane of the nebula, as defined by the rotational angular momentum vector of the orginal cloud core. As a result, the grains settle toward the central plane.

As the grains settle, they begin to collide with one another. The grains stick and quickly grow from microscopic to macroscopic objects, perhaps meters in size (initial agglomerations of grains may look very much like the suspected cometary IDP in Fig. 9). This process continues and even increases as the grains reach the denser environment at the central plane of the nebula. The meter-sized bodies grow to kilometer-sized bodies, and these bodies grow to 100 km-sized bodies. These bodies are known as planetesimals. As a planetesimal begins to acquire significant mass, its cross section for accretion grows beyond its physical cross section because it is now capable of gravitationally deflecting smaller planetesimals toward it. These larger planetesimals then "run away" from the others, growing at an ever-increasing rate.

The actual process is far more complex than described here, and many details of this scenario still need to be worked out. For example, the role of turbulence in the nebula is not well quantified. Turbulence would tend to slow or even prevent the accretion of grains into larger objects. Also, the role of electrostatic and magnetic effects in the nebula are not understood.

Nevertheless, it appears that accretion in the central plane of the solar nebula can account for the growth of planets from interstellar grains. An artist's concept of the accretion disk in the solar nebula is shown in Fig. 12. In the inner region of the solar nebula, close to the forming Sun, the higher temperatures would vaporize icy and organic grains, leaving only silicate grains to form the planetesimals, which eventually merged to form the terrestrial planets. At larger distances where the nebula was cooler, organic and icy

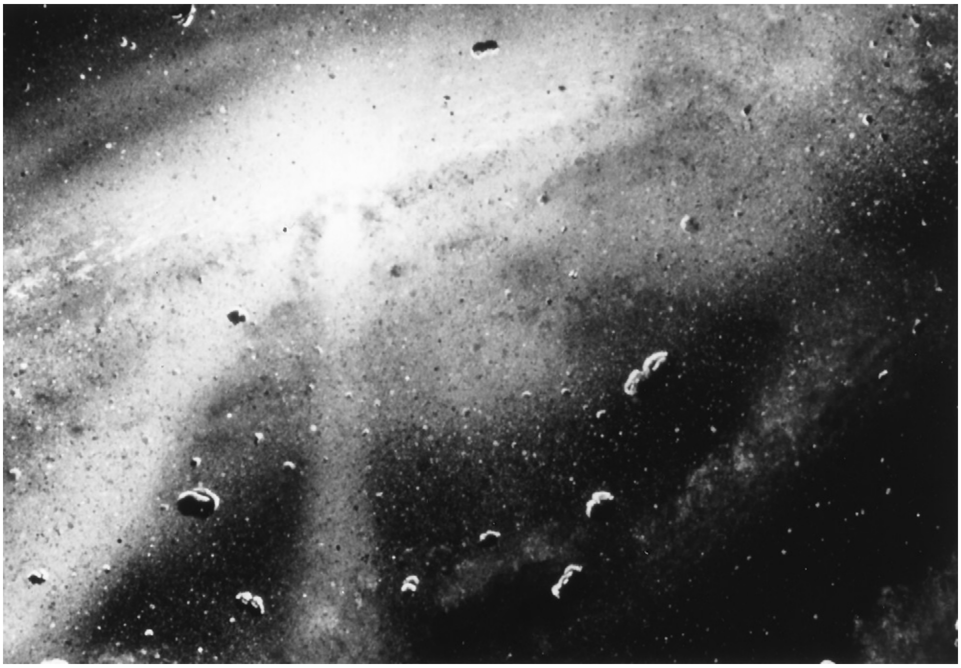


FIGURE 12 Artist's concept of the accretion disk in the solar nebula, showing the orbiting planetesimals and the proto-Sun at the center. (Painting by William Hartmann.)

grains would condense and these would combine with the silicates to form the cores of the giant planets. Because the total mass of ice and organics may have been several times the mass of silicates, the cores of the giant planets may actually have grown faster than the terrestrial planets interior to them.

At some point, the growing cores of the giant planets became sufficiently massive to begin capturing hydrogen and helium directly from the nebula gas. Because of the lower temperatures in the outer planets zone, the giant planets were able to retain the gas and continue to grow even larger. The terrestrial planets close to the Sun may have acquired some nebula gas, but likely could not hold on to it at their higher temperatures.

Observations of protostars in nearby molecular clouds have found substantial evidence for accretionary disks and gas nebulae surrounding these stars. The relative ages of these protostars can be estimated by comparing their luminosity and color with theoretical predictions of their location in the Hertzsprung–Russell diagram. One of the more interesting observations is that the nebula dust and gas around solar-mass protostars seem to dissipate after about 10^7 years. It appears that the nebula and dust may be swept away by mass outflows, essentially superpowerful solar winds, from the protostars. If the Sun formed similarly to the protostars we see today, then these observations set strong limits on the likely formation times of Jupiter and Saturn.

An interesting process that must have occurred during the late stages of planetary accretion is "giant impacts," that is, collisions between very large protoplanetary objects. As noted in Section II. C, a giant impact between a Mars-sized protoplanet and the proto-Earth is now the accepted explanation for the origin of the Earth's Moon. Giant impacts have similarly been invoked to explain the high mean density of Mercury, the retrograde rotation of Venus, the high obliquity of Uranus, and possibly even the formation of the Pluto–Charon binary. Although it was previously thought that such giant impacts were low-probability events, they are now recognized to be a natural consequence of the final stages of planetary accretion.

Another interesting process late in the accretion of the planets is the clearing of debris from the planetary zones. At some point in the growth of the planets, their gravitational spheres of influence grew sufficiently large that an encounter with a planetesimal would more likely lead to the planetesimal being scattered into a different orbit, rather than an actual collision. This would be particularly true for the massive Jovian planets, both because of their stronger gravitational fields and because of their larger distances from the Sun.

Since it is just as likely that a planet will scatter objects inward as outward, the clearing of the planetary zones resulted in planetesimals being flung throughout the solar system, and in a massive bombardment of all planets and satellites. Many planetesimals were also flung out of the planetary system to interstellar space, or to distant orbits in the Oort cloud. Although the terrestrial planets are generally too small to eject objects out of the solar system, they can scatter objects to Jupiter-encountering orbits where Jupiter will quickly dispose of them.

The clearing of the planetary zones has several interesting consequences. The dynamical interaction between the planets and the remaining planetesimals results in an exchange of angular momentum. Computer-based dynamical simulations have shown that this causes the semimajor axes of the planets to migrate radially. In general, Saturn, Uranus, and Neptune are expected to first move inward and then later outward as the ejection of material progresses. Jupiter, which ejects the most material because of its huge mass, migrates inward, but only by a few tenths of an astronomical unit.

This migration of the giant planets has significant consequences for the populations of small bodies in the planetary region. As the planets move, the locations of their mean motion and secular resonances will move with them. This will result in some small bodies being captured into resonances while others will be thrown into chaotic orbits, leading to their eventual ejection from the system or possibly to impacts on the planets and the Sun. The radial migration of the giant planets has been invoked in the clearing of both the outer regions of the main asteroid belt and the inner regions of the Kuiper belt.

Another consequence of the clearing of the planetary zones is that rocky planetesimals formed in the terrestrial planets zone will be scattered throughout the Jovian planets region, and vice versa for icy planetesimals formed in the outer planets zone. The bombardment of the terrestrial planets by icy planetesimals is of particular interest, both in explaining the Late Heavy Bombardment and as a means of delivering the volatile reservoirs of the terrestrial planets. Isotopic studies suggest that some fraction of the water in the Earth's oceans may have come from comets, though not all of it. Also, the recent discovery of an asteroidal-appearing object, 1996 PW, on a long-period comet orbit has provided evidence that asteroids may indeed have been ejected to the Oort cloud, where they may make up 1–3% of the population there.

IV. THE SOLAR SYSTEM'S PLACE IN THE GALAXY

The Milky Way is a large, spiral galaxy, about 30 kpc in diameter. Some parts of the galactic disk can be traced out to 25 kpc from the galactic center, and the halo can be traced to 50 kpc. The galaxy contains approximately 100 billion stars and the total mass of the galaxy is estimated to be about 4×10^{11} solar masses ($M_{\odot}$). Approximately 25% of the mass of the galaxy is estimated to be in visible stars, about 15% in stellar remnants (white dwarfs, neutron stars, and black holes), 25% in interstellar clouds and interstellar material, and 35% in "dark matter." Dark matter is a general term used to describe unseen mass in the galaxy, which is needed to explain the observed dynamics of the galaxy (i.e., stellar motions, galactic rotation) but which has not been detected through any available means. There is considerable speculation about the nature of the dark matter, which includes everything from exotic nuclear particles to brown dwarfs (substellar objects, not capable of nuclear burning) and dark stars (the burned-out remnants of old stars) to massive black holes. The galaxy is estimated to have an age of 10 to 15 billion years, equal to the age of the universe.

The Milky Way galaxy consists of four major structures: the galactic disk, the central bulge, the halo, and the corona (Fig. 13). As the name implies, the disk is a highly flattened, rotating structure about 15 kpc in radius and about 0.5–0.8 kpc thick, depending on which population of stars is used to trace the disk. The disk contains relatively young stars and interstellar clouds, arranged in a multi-arm spiral structure (Fig. 14). At the center of the disk is the bulge, an oblate spheroid about 3 kpc in radius in the plane of the disk, and with a radius of about 1.5 kpc perpendicular to the disk. The bulge rotates more slowly than the disk, and consists largely of densely packed older stars and interstellar clouds. It does not display spiral structure. At the center of the bulge is the nucleus, a complex region only 4–5 pc across, which appears to have a massive black hole at its center. The mass of the central black hole has been estimated at 2.6 million $M_{\odot}$.

The halo surrounds both of these structures and extends ~20 kpc from the galactic center. The halo has an oblate spheroid shape and contains older stars and globular clusters of stars. The corona appears to be a yet more distant halo at 60–100 kpc and consists of dark matter, unobservable except for the effect it has on the dynamics of observable bodies in the galaxy. The corona may be several times more massive than

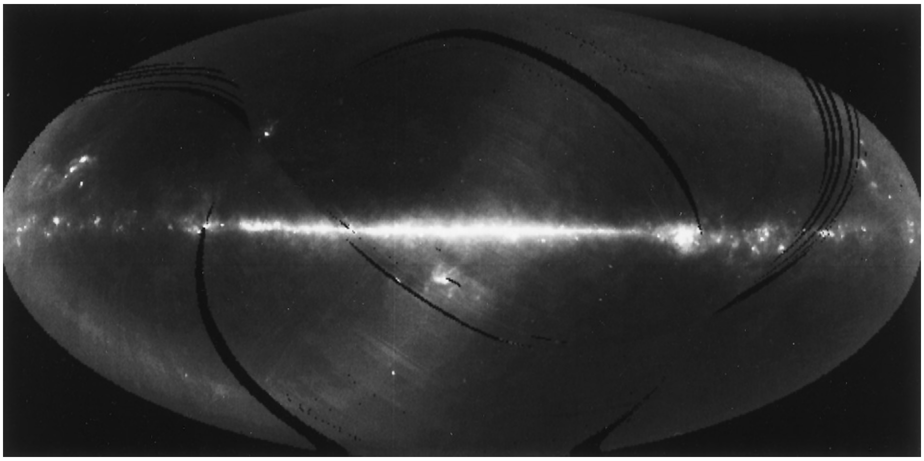


FIGURE 13 An image of the sky at infrared wavelengths as constructed from *IRAS* satellite data. The Milky Way galaxy is visible as the bright horizontal band through the image, with the galactic bulge at the center of the image. The fainter, S-shaped structure extending from lower left to upper right is the zodiacal dust cloud in the ecliptic plane. The plane of the ecliptic is tilted 62° to the plane of the galaxy. Dark gores are gaps in the data caused by incomplete scans by *IRAS*.

the other three galactic components combined. Many descriptions of the galaxy include the halo and the corona as a single component.

The galactic disk is visible in the night sky as the Milky Way, a bright band of light extending around the celestial sphere. When examined with a small telescope, the Milky Way is resolved into thousands or even millions of individual stars, and numerous nebulae and star clusters. The direction to the center of the galaxy is in the constellation Sagittarius (best seen from the Southern Hemisphere in June) and the disk appears visibly wider in that direction, which is the view of the central bulge.

The disk is not perfectly flat; there is evidence for warping in the outer reaches of the disk, between 15 and 25 kpc. The warp may be the result of gravitational

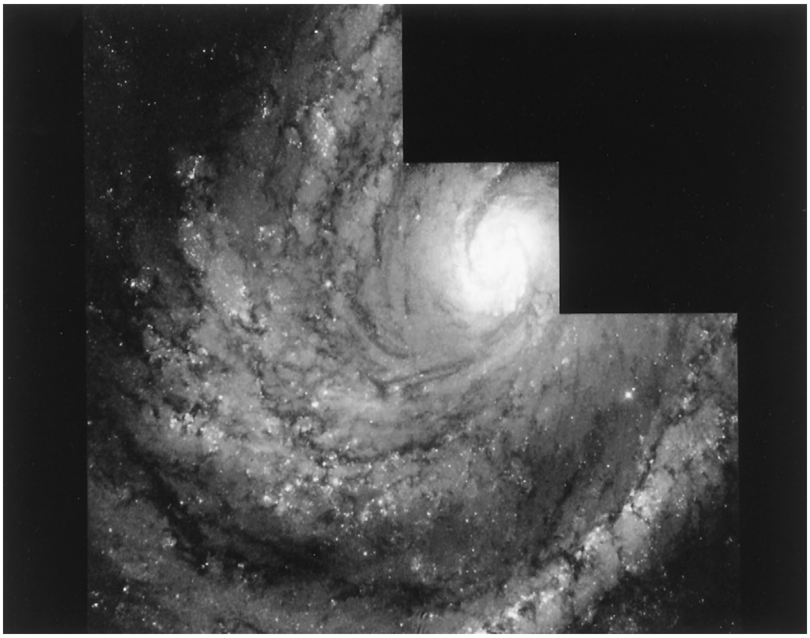


FIGURE 14 Messier 100, a large spiral galaxy in the constellation Coma Berenices, as photographed by the *Hubble Space Telescope*. The Milky Way galaxy may appear similar to this.

perturbations due to encounters with other galaxies, and/or with the Magellanic clouds, two nearby, irregular dwarf galaxies that appear to be in orbit around the Milky Way. Similarly, evidence has been building in recent years that the bulge is not an oblate spheroid, but rather appears to have a triaxial shape. This type of structure is observed in external galaxies and is referred to as a "bar"; such galaxies are known as barred spirals. In addition, the Milky Way's central bar appears to be tilted relative to the plane of the galactic disk. The nonspherical shape of the bulge and the tilt have important implications for understanding stellar dynamics and the long-term evolution of the galaxy.

Stars in the galactic disk have different characteristic velocities as a function of their stellar classification, and hence age. Low-mass, older stars, like the Sun, have relatively high random velocities and as a result can move farther out of the galactic plane. Younger, more massive stars have lower mean velocities and thus smaller scale heights above and below the plane. Giant molecular clouds, the birthplace of stars, also have low mean velocities and thus are confined to regions relatively close to the galactic plane. The disk rotates clockwise as viewed from "galactic north," at a relatively constant velocity of 160–220 km sec^{-1}. This motion is distinctly non-Keplerian, the result of the very nonspherical mass distribution. The rotation velocity for a circular galactic orbit in the galactic plane defines the Local Standard of Rest (LSR). The LSR is then used as the reference frame for describing local stellar dynamics.

The Sun and the solar system are located approximately 8.5 kpc from the galactic center, and 10–20 pc above the central plane of the galactic disk. The circular orbit velocity at the Sun's distance from the galactic center is 220 km sec^{-1}, and the Sun and the solar system are moving at approximately 17 to 22 km sec^{-1} relative to the LSR. The Sun's velocity vector is currently directed toward a point in the constellation of Hercules, approximately at right ascension $18^h\,0^m$ and declination $+30°$, known as the solar apex. Because of this motion relative to the LSR, the solar system's galactic orbit is not circular. The Sun and planets move in a quasi-elliptical orbit between about 8.4 and 9.7 kpc from the galactic center, with a period of revolution of about 240 million years. The solar system is currently close to and moving inward toward "perigalacticon," the point in the orbit closest to the galactic center. In addition, the solar system moves perpendicular to the galactic plane in a harmonic fashion, with a period of 52 to 74 million years and an amplitude of ± 49 to 93 pc out of the galactic plane. (The uncertainties in the estimates of the period and amplitude of the motion are caused by the uncertainty in the amount of dark matter in the galactic disk.) The Sun and planets passed through the galactic plane about 2–3 million years ago, moving "northward."

The Sun and solar system are located at the inner edge of one of the spiral arms of the galaxy, known as the Orion or local arm. Nearby spiral structures can be traced by constructing a three-dimensional map of stars, star clusters, and interstellar clouds in the solar neighborhood. Two well-defined neighboring structures are the Perseus arm, farther from the galactic center than the local arm, and the Sagittarius arm, toward the galactic center. The arms are about 0.5 kpc wide and the spacing between the spiral arms is about 1.2–1.6 kpc. The local galactic spiral arm structure is illustrated in Fig. 15.

The Sun's velocity relative to the LSR is low as compared with other G-type stars, which have typical velocities of 40–45 km sec^{-1} relative to the LSR. Stars are accelerated by encounters with giant molecular clouds in the galactic disk. Thus, older stars can be accelerated to higher mean velocities, as noted earlier. The reason(s) for the Sun's low velocity are not known. Velocity-altering encounters with giant molecular clouds occur with a typical frequency of once every 300–500 million years.

The local density of stars in the solar neighborhood is about 0.11 pc^{-3}, though many of the stars are in binary or multiple star systems. The local density of single, binary, and multiple star systems is 0.086 pc^{-3}. Most of these are low-mass stars, less massive and less luminous than the Sun. The nearest star to the solar system is Proxima Centauri, which is a low-mass ($M \simeq 0.1M_\odot$), distant companion to Alpha Centauri, which itself is a double-star system of two close-orbiting solar-type stars. Proxima Centauri is currently about 1.3 pc from the Sun and about 0.06 pc (1.3×10^4 AU) from the Alpha Centauri pair it is orbiting. The second nearest star is Barnard's star, a fast-moving red dwarf at a distance of 1.83 pc. The brightest star within 5 pc of the Sun is Sirius, an A1 star ($M \simeq 2M_\odot$) about 2.6 pc away. Sirius also is a double star, with a faint, white dwarf companion. The stars in the solar neighborhood are shown in Fig. 16.

The Sun's motion relative to the LSR, as well as the random velocities of the stars in the solar neighborhood, will occasionally result in close encounters between the Sun and other stars. Using the foregoing value for the density of stars in the solar neighborhood, one can predict that about 12 star systems (single or multiple stars) will pass within 1 pc of the Sun per million years. The total number of stellar encounters scales as the square of the encounter distance. This rate

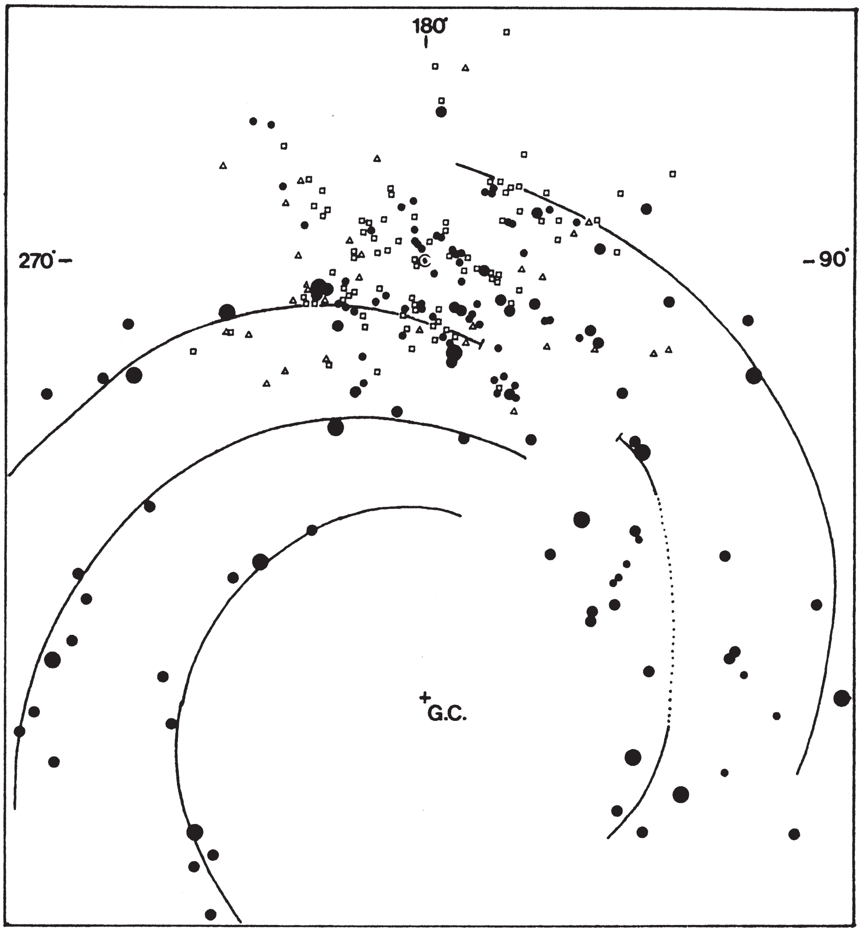


FIGURE 15 The spiral structure of the Milky Way galaxy as inferred from the positions of H II regions (clouds of ionized hydrogen) in the galaxy. The Sun and solar system are located at the upper center, as indicated by the ⊙ symbol. (Reprinted with kind permission from Kluwer Academic Publishers, Forbes and Shuter, *in* "Kinematics, Dynamics and Structure of the Milky Way," p. 221, Fig. 3, copyright © 1983.)

has been confirmed in part by data from the *Hipparcos* astrometry satellite, which measured the distances and proper motions of ~118,000 stars and which was used to reconstruct the trajectories of stars in the solar neighborhood.

Based on this rate, the closest stellar approach over the lifetime of the solar system would be expected to be at ~900 AU. Such an encounter would result in a major perturbation of the Oort cloud and would eject many comets to interstellar space. It would also send a shower of comets into the planetary region, raising the impact rate on the planets for a period of about 2–3 million years, and having other effects that may be detectable in the stratigraphic record on the Earth or on other planets. A stellar encounter at 900 AU could also have a substantial perturbative effect on the orbits of comets in the Kuiper belt and would likely disrupt the outer regions of that ecliptic comet disk. Obviously, the effect that any such stellar passage will have is a strong function of the mass and velocity of the passing star.

The advent of space-based astronomy, primarily through Earth-orbiting ultraviolet and X-ray telescopes, has made it possible to study the local interstellar medium surrounding the solar system. The structure of the local interstellar medium has turned out to be quite complex. The solar system appears to be on the edge of an expanding bubble of hot plasma about 120 pc in radius, which appears to have originated from multiple supernovae explosions in the Scorpius–Centaurus OB association. The Sco–Cen association is a nearby star-forming region that contains many young, high-mass O- and B-type stars. Such stars have relatively short lifetimes and end their lives in massive supernova explosions, before collapsing into black holes. The expanding shells of hot gas blown off the

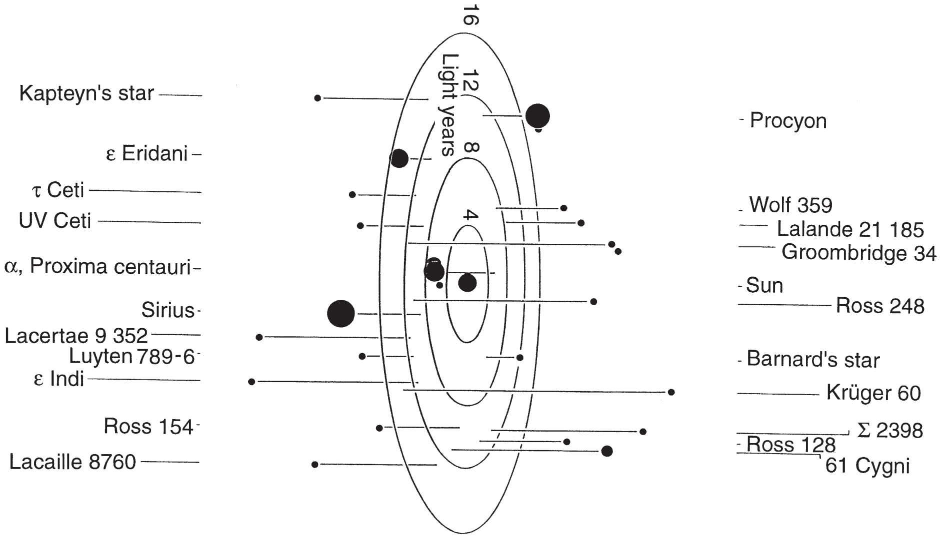


FIGURE 16 A three-dimensional representation of the stars in the solar neighborhood. Horizontal lines indicate the relative distance of the stars north (to the right) or south (to the left) of the celestial equator. The size of the dot representing each star denotes its relative brightness. [From Gilmore, G.F., *in* "Astronomy and Astrophysics Encyclopedia," S. P. Maran, Ed. Copyright © 1992 John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]

stars in the supernova explosions are able to "sweep" material before them, leaving a low-density "bubble" of hot plasma.

Within this bubble, known as the Local Bubble, the solar system is at this time within a small interstellar cloud, perhaps 2–5 pc across, known as the Local Interstellar Cloud. That cloud is apparently a fragment of the expanding shells of gas from the supernova explosions, and there appear to be a number of such clouds within the local solar neighborhood.

V. THE FATE OF THE SOLAR SYSTEM

Stars like the Sun are expected to have lifetimes on the main sequence of about 10 billion years. The main sequence lifetime refers to the time period during which the star produces energy through hydrogen fusion in its core. As the hydrogen fuel in the core is slowly depleted over time, the core contracts to maintain the internal pressure. This raises the central temperature and, as a result, the rate of nuclear fusion also increases and the star slowly brightens. Thus, temperatures throughout the solar system will slowly increase over time. Presumably, this slow brightening has already been going on since the formation of the Sun and solar system.

A $1M_{\odot}$ star like the Sun is expected to run out of hydrogen at its core in about 10 billion years. As the production of energy declines, the core again contracts. The rising internal temperature and pressure are then able to ignite hydrogen burning in a shell surrounding the depleted core. The hydrogen burning in the shell heats the surrounding mass of the star and causes it to expand. The radius of the star increases and the surface temperature drops. The luminosity of the star increases dramatically and it becomes a red giant. Eventually the star reaches a brightness about 10^3 times more luminous than the present-day Sun, a surface temperature of 3000 K, and a radius of 100–200 solar radii. A distance of one hundred solar radii is equal to 0.46 AU, larger than the orbit of Mercury. Two hundred radii is just within the orbit of the Earth. Thus, Mercury and likely Venus will be incorporated into the outer shell of the red giant Sun and will be vaporized.

The increased solar luminosity during the red giant phase will result in a fivefold rise in temperatures throughout the solar system. At the Earth's orbit, this temperature increase will vaporize the oceans and roast the planet at a temperature on the order of ~1400 K or more. At Jupiter's orbit it will melt the icy Galilean satellites and cook them at a more modest temperature of about 600 K, about the same as current noontime temperatures on the surface of Mercury. Typical temperatures at the orbit of Neptune will be about the same as they are today at the orbit of the Earth. Comets in the inner portion of the Kuiper belt will be warmed sufficiently to produce visible comae.

The lowered gravity at the surface of the greatly expanded Sun will result in a substantially increased